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PUBLICATIONS

OF THE

Earthquake Investigation Committee

IN

FOREIGN LANGUAGES.

NO. 22 A.

TOKYO, 1908.

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PUBLICATIONS OF THE EARTHQUAKE INVESTIGATION
COMMITTEE. NO. 22. SECTION A.

Observation of Local Earthquakes on Mount Tsukuba, in 1905.

By

F. Omori, Sc. D.,

Member of the Imperial Earthquake Investigation Committee.

With Pls. I—VI.

Place of observation. The present paper is a preliminary report on the seismometrical measurements made in 1905 at H.I.H. Prince Yamashina's meteorological station at Tsukuba, a small town at mid-height of the southern slope of the Tsukuba-san. The latter is a mountain of granite and diorite formations, which is situated in the south-western part of the province of Hitachi, and which rises, almost as a solitary mass, to an elevation of 870 metres, directly out from the low plain bordering the lower course of the river Tone and the Kasumiga-ura. The geographical position of the meteorological station in question, which is 240 metres above the sea level, is $\varphi=36°\ 12'\ 22''$ N., $\lambda=140°\ 5'\ 56''$ E. A full account of these earthquake observations as well as those made at His Highness' Meteorological Observatory, established in 1901, at the top of one of the double peaks of the Tsukuba-san, will be given as an appendix to the "Ergebnisse der meteorologischen Beobachtungen auf dem Tsukubasan."

Instrument. The observations, whose object was the study of the near earthquakes, were made with an EW component

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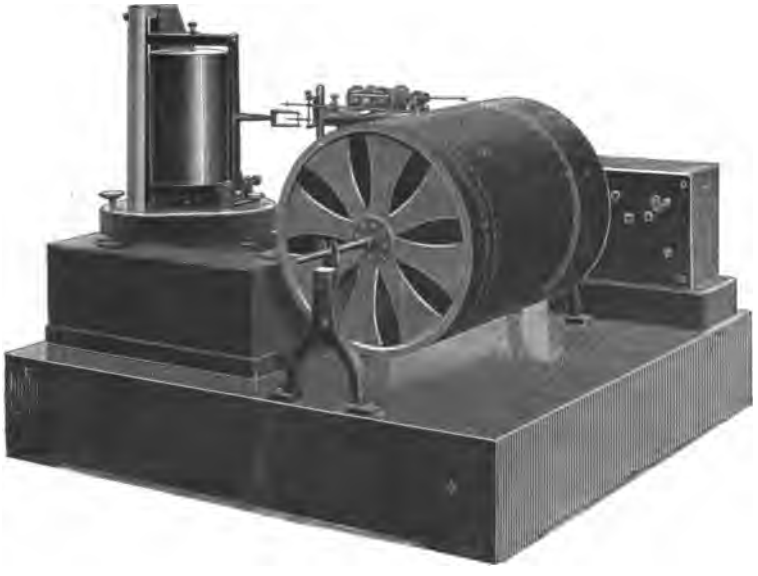
horizontal tremor-recorder*, (shown in the accompanying figure), whose instrumental constants were as follows:

Weight of the heavy bob=about 15 kg.
Multiplication ratio of the pointer=90.
Natural period of the horizontal pendulum=about 4 sec.
Rate of motion of the smoked paper wrapped round the revolving drum=about 8–16 mm per minute.

As the town of Tsukuba is very quiet and free from the effect of traffic and similar artificial disturbances, the site of the meteorological station is particularly well adapted to the observation of the small local shocks; there being no great amount of the pulsatory oscillations, due to the rocky nature of the mountain. On account of the same latter circumstance, the majority of the sensible earthquakes were preceded or accompanied by sounds.



* This instrument is similar to those described in the "Publications," No. 18, and the "Bulletin," Vol. I, No. 4.

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The observations have been carried on by Mr. J. Sato, chief observer of the Tsukuba observatories, Mr. H. Tsutsui, assistant observer, and others.

***List of the earthquakes observed in* 1905.** The tremor-recorder is sensible only to the quicker component of the seismic motion, and recorded, in 1905, four hundred and eighty-seven earthquakes, whose epicentral distances were each less than 1,000 km, which is nearly equal to the distance of the Tsukuba-san from either the north-eastern end of Hokkaido on the north, or the northern part of Kyushu on the south-west. The accompanying list gives for the EW component of each of these shocks the following particulars:—

(1) Date.
(2) Time of earthquake occurrence, given in the 1st Normal Japan Time, or that of longitude 135° E. of Greenwich.
(3) Intensity of motion, distinguished as *slight*, or *moderate*. None of the earthquakes was *strong* or destructive.*
(4) Total duration.
(5) Duration of the preliminary tremor.
(6) Maximum range of motion in the preliminary tremor.
(7) ,, ,, ,, ,, principal portion.
(8) Remarks.

The preliminary tremor was in most cases quite sharply defined.

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* The intensity of the non-destructive earthquake motion is indicated as slight, moderate, or strong. A slight shock is one which is very feeble and just enough to be felt; a moderate shock is one whose motion is well-pronounced but not so severe as to cause general alarm; and a strong shock is one which is sufficiently intense to cause people to run out of doors, to overturn furnitures, etc.

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List of 487 Earthquakes observed on Mount Tsukuba in 1905.

(* denotes an *insensible* shock.)

Date.	Time of Occurrence.	Intensity.	Total Duration.	Duration of Prel. Tremor.	Max. Motion in Prel. Tremor.	Max. Motion in Principal Portion.	Remarks.
	January.						
1	h m s 4 30 30 a.m.	Slight.	sec. 106	sec. 16.4	mm. 0.010	mm. 0.082	
,,	8 53 10 p.m.	Do.	26	14.2	—	0.013	
2	2 27 25 a.m.	*	37	11.3	—	0.006	
,,	4 25 30 a.m.	*	31	8.2	0.007	0.014	
5	0 25 06 a.m.	Slight.	30	5.6	0.004	0.028	Accompanied by loud sound.
7	10 57 00 a.m.	Moderate.	64	9.9	0.013	0.033	
9	4 00 50 p.m.	*	29	9.4	—	0.009	Sound only perceived.
11	1 23 10 a.m.	*	23	8.7	—	0.011	Do.
13	11 25 30 a.m.	Slight.	23	6.0	0.006	0.044	Accompanied by sound.
14	1 09 00 p.m.	*	40	41.0	—	0.002	
,,	5 38 30 p.m.	Moderate.	65	5.9	0.004	0.058	Accompanied by sound.
17	4 19 00 a.m.	Slight.	22	6.7	0.015	0.080	
,,	10 59 20 a.m.	Do.	36	10.4	—	0.008	Accompanied by sound.
21	7 44 27 a.m.	Do.	35	5.9	—	0.011	Accompanied by loud sound.
,,	5 29 00 p.m.	*	70	6.0	—	0.004	Sound only perceived.
22	2 53 00 a.m.	Slight.	78	13.1	0.008	0.026	
,,	0 58 40 p.m.	*	16	8.1	—	0.039	
25	8 30 37 p.m.	Slight.	31	8.4	0.011	0.060	
26	1 55 15 p.m.	*	—	10.3	—	—	
,,	4 02 30 p.m.	Moderate.	106	11.0	0.028	0.220	
,,	5 19 28 p.m.	*	120	46.0	—	0.003	
,,	7 14 10 p.m.	*	90	(?)	—	0.004	Origin distant.
27	9 23 10 p.m.	*	60	(?)	—	0.002	Do.

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Date.	Time of Occurrence.	Intensity.	Total Duration.	Duration of Prel. Tremor.	Max. Motion in Prel. Tremor.	Max. Motion in Principal Portion.	Remarks.
	January.						
	h m s		sec.	sec.	mm.	mm.	
28	1 48 30 a.m.	*	30	6.6	—	—	
	February.						
2	8 17 00 a.m.	*	133	63.0	—	0.010	
„	9 08 25 a.m.	Slight.	98	24.0	—	0.022	
4	0 54 30 a.m.	Do.	30	9.5	0.020	0.037	
5	3 58 00 p.m.	*	35	11.6	—	0.022	
6	5 21 00 a.m.	*	40	16.8	—	0.017	
7	11 33 00 a.m.	*	85	22.5	—	0.011	
„	2 46 45 p.m.	Moderate.	100	17.0	0.036	0.120	
„	8 49 05 p.m.	Slight.	20	0.0	—	0.072	Accompanied by loud sound.
11	7 05 30 a.m.	Moderate.	70	25.0	0.022	0.073	Accompanied by sound.
13	1 55 10 p.m.	Slight.	32	8.0	—	0.010	Do.
14	10 55 45 p.m.	Moderate.	140	18.5	0.001	0.047	Do.
15	10 13 00 a.m.	*	65	16.4	—	0.022	
„	5 29 30 p.m.	Slight.	66	7.1	0.011	0.038	Accompanied by sound.
„	9 12 00 p.m.	*	20	0.0	—	0.022	
17	2 06 40 a.m.	Slight.	21	0.0	—	—	Accompanied by sound.
„	3 27 25 a.m.	Do.	87	19.5	0.009	0.054	Do.
„	10 56 30 a.m.	*	14	8.0	—	0.016	Do.
„	5 14 25 p.m.	Slight.	72	5.7	0.013	0.076	Do.
„	6 44 20 p.m.	Moderate.	144	14.1	0.027	0.180	Do.
18	6 56 05 p.m.	Slight.	100	10.1	—	0.024	Do.
„	7 08 10 p.m.	*	36	13.2	—	—	Sound only perceived.
20	1 47 33 p.m.	Slight.	24	8.5	0.012	0.064	Accompanied by sound.
21	2 26 30 p.m.	*	44	0.0	—	—	Sound only perceived.
23	9 03 20 a.m.	*	46	6.0	—	—	Do.

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Date.	Time of Occurrence.	Intensity.	Total Duration.	Duration of Prel. Tremor	Max. Motion in		Remarks.
					Prel. Tremor.	Principal Portion.	
	February.						
	h m s		sec.	sec.	mm.	mm.	
23	11 35 00 p.m.	*	24	9.2	0.004	0.010	
24	4 18 50 a.m.	Slight.	40	14.1	0.004	0.038	
25	2 45 00 a.m.	*	34	7.7	—	0.010	
„	3 13 00 a.m.	*	—	—	—	—	Only loud sound perceived.
„	6 44 15 a.m.	Moderate.	47	14.3	0.017	0.098	Accompanied by sound.
„	0 54 00 p.m.	*	22	7.0	0.003	0.008	
27	1 19 45 a.m.	Slight.	59	12.1	0.009	0.036	Accompanied by sound.
	March.						
3	4 12 05 p.m.	*	53	6.0	0.004	0.012	
„	5 17 40 p.m.	*	20	7.1	—	0.014	
4	3 39 45 a.m.	Slight.	43	8.9	—	0.024	Accompanied by sound.
„	9 18 30 p.m.	Moderate.	76	9.0	0.022	0.170	Do.
6	6 04 25 a.m.	Slight.	40	8.2	0.004	0.047	Accompanied by sound.
„	6 08 15 a.m.	Do.	65	8.8	0.004	0.060	Do.
8	7 04 00 a.m.	*	47	15.3	—	0.012	
9	3 33 00 a.m.	Slight.	183	14.6	0.024	0.057	Accompanied by sound.
12	8 19 30 a.m.	Do.	34	11.3	0.002	0.014	Do.
„	8 12 30 p.m.	Do.	21	6.2	0.020	0.043	Do.
14	4 10 45 p.m.	*	49	8.4	0.004	0.028	
„	7 16 40 p.m.	*	33	11.0	—	0.006	
16	1 06 11 p.m.	Slight.	41	9.4	0.024	0.044	Accompanied by sound.
18	1 09 35 p.m.	Do.	33	11.8	0.006	0.060	Do.
„	10 30 00 p.m.	Do.	27	7.0	—	0.039	Do.
19	11 11 30 p.m.	*	64	35.0	—	0.009	
21	2 58 20 a.m.	Slight.	63	7.8	—	0.021	Accompanied by sound.
„	10 57 25 a.m.	Do.	106	36.0	0.002	0.020	Do.

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Date.	Time of Occurrence.	Intensity.	Total Duration.	Duration of Prel. Tremor.	Max. Motion in Prel. Tremor.	Max. Motion in Principal Portion.	Remarks.
	March.						
	h m s		sec.	sec.	mm.	mm.	
23	7 02 25 a.m.	*	67	15.0	—	0.013	
„	5 59 00 p.m.	Slight.	40	13.1	0.007	0.038	Accompanied by sound.
24	11 16 00 a.m.	*	31	14.2	—	0.009	
25	2 00 00 a.m.	*	52	19.6	—	0.006	
26	8 04 00 a.m.	Slight.	30	3.5	—	0.028	Accompanied by sound.
„	9 33 30 p.m.	*	18	5.2	0.002	0.039	
	April.						
3	7 50 00 p.m.	*	94	13.6	—	—	
6	9 29 10 p.m.	Moderate.	68	6.7	0.093	0.490	Loud sound heard toward S., 5 or 6 sec. before the shock. Houses were much shaken, and liquids thrown out. The rain gauge was displaced slightly toward SW.
„	11 33 40 p.m.	*	39	6.3	0.008	0.029	
10	0 25 30 a.m.	*	34	9.6	0.004	0.021	
11	3 44 40 a.m.	*	21	0.9	—	0.036	
12	7 23 10 a.m.		19	6.0	0.003	0.042	Sound only perceived.
13	0 37 25 p.m.	*	51	17.2	—	0.016	
„	6 02 40 p.m.	Slight.	70	9.0	0.018	0.064	Loud sound heard toward S. before the shock.
14	1 00 00 a.m.	*	21	7.3	—	0.011	
„	7 37 00 a.m.	Slight.	48	25.2	—	0.044	
17	3 11 05 a.m.	*	31	7.8	—	0.028	
„	7 13 00 p.m.	*	123	65.0	—	0.006	
9	1 02 00 a.m.	*	10	5.6	—	0.006	
„	5 29 00 a.m.	*	35	10.3	—	0.004	
20	8 45 30 a.m.	*	45	17.4	—	0.016	
21	1 28 00 a.m.	*	24	7.4	—	0.011	
„	11 07 30 p.m.	*	42	7.7	—	0.006	

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Date.	Time of Occurrence.	Intensity.	Total Duration.	Duration of Prel. Tremor	Max. Motion in Prel. Tremor.	Max. Motion in Principal Portion.	Remarks.
	April.						
	h m s		sec.	sec.	mm.	mm.	
22	3 34 00 a.m.	*	84	17.3	—	0.008	
24	1 04 00 a.m.	*	85	22.2	—	0.016	
„	5 15 02 a.m.	Moderate.	65	15.7	0.017	0.153	Accompanied by sound.
„	6 31 00 a.m.	Do.	60	11.6	0.024	0.094	Do.
25	3 42 00 a.m.	*	45	8.5	—	0.016	
27	0 31 00 p.m.	Slight.	18	5.4	0.004	0.021	Loud sound heard toward SW.
29	7 17 30 a.m.	*	Very Short.	0.0	—	—	The diagram consisted only of a single stroke.
30	9 34 10 a.m.	*	50	12.2	0.013	0.024	
„	7 37 30 p.m	Slight.	25	4.9	—	0.036	Preceded by loud sound, which was heard toward S. The principal portion of the diagram lasted only 3.5 sec.
	May.						
2	3 00 45 p.m.	*	58	9.8	—	0.016	
4	5 51 50 p.m.	*	11	0.0	—	0.014	
5	4 04 05 a.m.	*	28	8.7	—	Small.	
„	8 13 20 a.m.	*	30	9.0	—	0.010	
7	6 27 00 p.m.	*	40	10.6	—	0.004	
„	10 20 10 p.m.	*	39	6.1	—	0.016	
„	10 24 20 p.m.	*	100	35.0	—	Small.	
8	8 12 55 p.m.	Moderate.	80	19.0	—	0.051	Accompanied by sound.
9	2 54 10 a.m.	Do.	143	11.0	0.051	0.204	Loud sound heard toward S.
13	7 32 00 p.m.	*	31	7.9	—	0.004	
15	8 07 25 a.m.	Slight.	68	9.2	0 017	0.061	Accompanied by sound.
16	2 51 00 a.m.	*	52	8.3	—	0.029	
17	2 06 30 a.m.	*	130	62.0	—	0.013	
„	8 32 10 a.m.	*	30	6.2	—	0.011	
„	10 03 00 a.m.	Slight.	43	5.3	0.006	0.044	

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Date.	Time of Occurrence.	Intensity.	Total Duration.	Duration of Prel. Tremor.	Max. Motion in Prel. Tremor.	Max. Motion in Principal Portion.	Remarks.
	May.						
	h m s		sec.	sec.	mm.	mm.	
20	4 53 30 p.m.	*	95	49.3	—	0.016	
22	6 23 30 p.m.	*	30	8.9	0.008	0.024	
23	5 18 15 a.m.	*	23	6.1	0.006	0.028	
,,	1 33 25 p.m.	*	20	7.4	—	0.028	
,,	7 45 00 p.m.	*	70	12.3	—	0.014	
24	8 32 30 p.m.	Slight.	109	41.0	—	0.024	
25	1 29 30 a.m.	Do.	41	5.2	0.009	0.077	
26	2 00 25 a.m.	Do.	60	10.1	0.010	0.058	Accompanied by sound.
,,	3 46 50 p.m.	Moderate.	107	19.4	0.043	0.160	Loud sound heard toward S., 3 sec. before the shock.
28	0 50 00 a.m.	*	17	—	—	Small.	
,,	1 49 00 a.m.	*	18	—	—	,,	
31	8 56 00 p.m.	*	65	12.0	0.002	0.011	
	June.						
2	1 17 50 p.m.	*	27	8.3	—	0.017	
3	0 44 30 a.m.	*	53	15.0	—	0.006	
,,	11 21 30 a.m.	Slight.	53	8.8	0.004	0.016	Accompanied by sound.
4	8 45 30 a.m.	*	70	6.4	—	0.003	
5	8 43 30 a.m.	*	35	?	—	0.008	
,,	10 01 30 a.m.	*	25	8.9	—	0.008	
6	0 40 00 a.m.	*	28	?	—	Small.	
,,	0 43 00 a.m.	*	31	19.6	—	0.007	
,,	1 13 00 a.m.	*	55	19.1	—	0.009	
,,	1 18 00 a.m.	*	40	?	—	0.004	
6	1 49 00 a.m.	*	57	18.0	—	0.013	
,,	2 04 00 a.m.	*	62	21.2	—	0.019	
,,	2 25 00 a.m.	*	60	17.8	—	0.008	

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Date.	Time of Occurrence.	Intensity.	Total Duration.	Duration of Prel. Tremor.	Max. Motion in		Remarks.
					Prel. Tremor.	Principal Portion.	
	June.						
6	h m s 2 27 00 a.m.	*	sec. 60	sec. ?	mm. —	mm. Small.	
„	5 17 00 a.m.	*	58	20.3	—	0.009	
„	5 57 30 a.m.	Moderate.	54	7.0	0.013	0.106	Loud sound heard toward SW.
„	9 19 00 a.m.	*	8	?	—	Small.	
„	9 23 00 a.m.	*	27	?	—	0.009	
„	11 45 30 a.m.	*	10	?	—	Small.	
7	6 12 30 a.m.	Moderate.	74	6.1	0.032	0.190	Loud sound heard toward SW.
„	2 39 50 p.m.	Do.	75	17.7	0.027	0.093	Loud sound heard toward SE.
„	2 41 05 p.m.	Slight.	91	17.2	0.027	0.083	
„	3 28 50 p.m.	*	10	?	—	Small.	
„	3 41 50 p.m.	*	7	?	—	„	
„	3 42 30 p.m.	*	—	18.3	—	0.008	
„	10 05 30 p.m.	*	40	16.7	—	0.031	
10	3 09 50 p.m.	Slight.	106	36.4	0.017	0.042	Accompanied by sound.
11	11 50 10 p.m.	Moderate.	49	5.6	0.066	0.220	Loud sound heard toward SW., 3 sec. before the shock.
12	5 17 30 p.m.	Do.	154	18.4	0.054	0.190	Sound heard toward S., 5 sec. before the shock, and ceased during the motion.
13	2 48 30 p.m.	*	95	29.0	—	Small.	
14	8 44 30 a.m.	*	28	11.1	—	0.012	
16	7 08 20 p.m.	*	20	?	—	Small.	Origin distant.
17	2 12 00 a.m.	*	20	7.7	—	0.007	
„	5 33 00 a.m.	*	30	?	—	Small.	Origin distant.
18	1 16 24 a.m.	Moderate.	100	13.2	0.023	0.190	Accompanied by sound.
„	2 15 30 a.m.	*	15	?	—	Small.	Origin distant.
„	3 33 15 a.m.	*	25	?	—	0.013	Do.
„	9 50 00 a.m.	*	10 ?	?	—	0.016	Do.
„	11 02 00 a.m.	*	5	?	—	0.021	The diagram consisted of a single stroke.

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Date.	Time of Occurrence.	Intensity.	Total Duration.	Duration of Prel. Tremor.	Max. Motion in		Remarks.
					Prel. Tremor	Principal Portion	
	June.						
	h m s		sec.	sec.	mm.	mm.	
19	6 38 30 a.m.	Slight.	18	6.6	—	0.027	Accompanied by sound.
20	5 31 00 a.m.	Do.	75	18.3	0.007	0.050	Do.
„	0 34 10 p.m	*	15	6.1	—	0.010	
„	0 37 40 p.m.	*	145	114.0	—	0.009	
26	1 23 00 a.m.	Slight.	55	16.0	0.012	0.056	Accompanied by sound.
„	1 38 20 p.m.	Do.	50	13.3	0.008	0.039	Loud sound heard toward S.
27	1 09 30 a.m.	*	160	54.0	0.007	0.039	
„	3 17 10 a.m.	Slight.	50	12.1	0.028	0.183	Accompanied by sound.
„	3 46 30 p.m.	*	35	9.9	—	0.006	
29	10 29 00 a.m.	Slight.	30	8.1	0.002	0.008	Accompanied by sound.
„	4 59 00 p.m.	*	20	7.1	0.002	0.007	
	July.						
2	10 58 00 p.m.	*	10	?	—	0.002	
3	4 43 00 p.m.	*	30	17.8	—	0.008	
„	11 14 20 p.m.	*	40	10.3	—	0.002	
4	6 58 20 p.m.	*	?	13.1	—	0.013	
5	2 08 30 a.m.	*	30	13.2	0.003	0.007	
„	9 00 30 a.m.	*	60	?	0.006	0.011	Origin distant.
„	2 37 10 p.m.	Slight.	40	10.1	0.003	0.010	Sound heard toward S.
7	1 21 25 a.m.	Moderate.	275	?	0.032	0.690	Origin distant. No sound.
„	1 26 00 a.m.	Slight.	95	32.0	0.012	0.071	
„	4 51 40 a.m.	*	35	?	—	0.010	Origin distant.
„	7 17 25 a.m.	Moderate.	225	62.0	0.077	0.170	Accompanied by sound.
„	9 06 30 a.m.	*	25	?	—	Small.	Origin distant.
„	10 19 00 a.m.	*	30	?	—	0.006	Do.
„	10 38 00 a.m.	*	100	60.0	0.006	0.011	

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Date.	Time of Occurrence.	Intensity.	Total Duration.	Duration of Prel. Tremor.	Max. Motion in		Remarks.
					Prel. Tremor.	Principal Portion.	
	July.						
7	h m s 9 27 45 p.m.	*	sec. 50	sec. 9.9	mm. —	mm. 0.016	
„	10 38 35 p.m.	*	70	?	—	0.013	Origin distant.
8	3 13 00 a.m.	*	70	37.5	—	0.014	
„	7 20 30 a.m.	*	20	?	—	Small.	Origin distant.
„	11 08 00 a.m.	*	50	23.0	—	0.018	
9	7 11 55 a.m.	Moderate.	160	29.3	0.050	0.150	Accompanied by weak sound.
„	7 21 30 a.m.	*	15	?	—	0.004	Origin distant.
„	11 23 00 a.m.	Slight.	45	9.1	—	0.040	Accompanied by loud sound.
10	2 49 20 a.m.	*	60	?	—	0.003	Origin distant.
„	7 55 00 a.m.	*	—	28.0	—	0.010	
11	4 55 00 a.m.	*	30	10.1	—	0.028	
„	6 18 25 a.m.	Slight.	105	22.5	0.012	0.048	Accompanied by sound.
12	0 38 25 a.m.	*	75	?	—	0.024	Origin distant.
„	0 41 00 a.m.	*	90	?	—	0.087	Do.
„	11 56 10 a.m.	*	21	4.7	0.002	0.004	Loud sound heard toward S.
13	5 05 15 a.m.	*	50	?	—	Small.	Origin distant.
„	1 53 00 p.m.	*	60	?	—	Do.	Do.
„	9 27 25 p.m.	*	40	?	—	0.004	Do.
14	6 02 30 a.m.	*	40	?	—	Small.	Do.
„	3 56 45 p.m.	*	75	18.2	—	0.011	
„	11 17 20 p.m.	*	—	9.5	—	0.003	
15	3 09 10 a.m.	Slight.	20	5.3	0.003	0.027	Accompanied by sound.
„	8 01 55 a.m.	Do.	60	11.5	0.004	0.033	Do.
„	7 07 30 p.m.	*	50	9.7	—	0.036	
16	3 38 25 p.m.	*	20	9.7	—	0.007	
„	4 08 30 p.m.	*	45	7.0	—	0.014	
19	3 27 30 a.m.	*	35	?	—	0.006	Origin distant.

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Date.	Time of Occurrence.	Intensity.	Total Duration.	Duration of Prel. Tremor	Max. Motion in		Remarks.
					Prel. Tremor	Principal Portion	
	July.						
	h m s		sec.	sec.	mm.	mm.	
19	5 03 12 p.m.	Moderate.	70	9.3	0.022	0.120	
„	6 39 00 p.m.	*	40	?	—	Small.	Origin distant.
20	4 33 15 a.m.	Slight.	25	5.7	—	0.022	Accompanied by sound.
„	5 35 20 a.m.	Do.	15	8.0	0.002	0.061	Do.
„	11 54 00 a.m.	Do.	30	4.4	0.027	0.082	Sound heard toward SW. before the shock.
„	5 49 10 p.m.	Slight.	55	?	—	0.028	
21	6 03 00 a.m.	*	75	10.9	—	0.039	
22	6 15 10 p.m.	*	70	28.0	—	0.007	
„	11 56 30 p.m.	*	26	?	—	Small.	Origin distant.
23	5 25 30 p.m.	Slight.	85	25.0	—	0.056	Accompanied by sound.
„	6 27 00 p.m.	Do.	40	19.7	—	0.051	Do.
„	7 00 20 p.m.	Moderate.	105	19.0	0.031	0.107	Sound heard toward S.
24	6 11 05 a.m.	*	60	?	—	Small.	Origin distant.
25	3 09 30 a.m.	*	45	?	—	0.017	Do.
26	0 49 20 a.m.	*	60	20.0	—	0.008	
„	1 04 30 a.m.	*	60	11.4	—	0.007	
„	4 30 07 a.m.	Slight.	55	6.2	0.016	0.073	Loud sound heard toward SW.
„	2 40 35 p.m.	Do.	65	16.0	—	0.022	
„	4 16 30 p.m.	*	60	20.5	—	0.028	
27	1 38 15 a.m.	Moderate.	100	7.9	0.039	0.340	Accompanied by loud sound.
„	2 09 30 p.m.	*	35	?	—	0.006	Origin distant.
29	4 57 30 a.m.	*	60	?	—	0.016	Do.
„	6 05 45 a.m.	Slight.	30	6.9	—	0.060	Loud sound heard toward SW., before the shock.
30	3 36 00 a.m.	*	90	58.0	—	0.007	
„	1 27 15 p.m.	*	?	32.5	—	Small.	
„	10 46 00 p.m.	*	30	?	—	Do.	Origin distant.

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Date.	Time of Occurrence.	Intensity.	Total Duration.	Duration of Prel. Tremor.	Max. Motion in		Remarks.
					Prel. Tremor.	Principal Portion.	
	August.						
	h m s		sec.	sec.	mm.	mm.	
1	8 08 30 a.m.	*	20	8.3	—	0.006	
2	4 24 30 a.m.	*	40	?	—	Small.	Origin distant.
„	2 17 50 p.m.	*	40	?	—	Do.	Do.
4	3 40 00 a.m.	*	95	30.0	0,008	0.018	
„	8 51 30 a.m.	*	85	30.0	0.008	0.024	
„	9 02 00 a.m.	*	60	30.0	—	Small.	
5	2 29 30 p.m.	*	45	—	—	Do.	Origin distant.
6	9 19 00 a.m.	*	40	?	—	0.006	
„	6 28 40 p.m.	*	50	12.2	—	0.006	
9	5 17 20 a.m.	Slight.	45	16.2	0.003	0.076	Accompanied by sound.
10	6 26 10 p.m.	*	55	15.7	—	0.012	
„	9 00 45 p.m.	*	50	?	—	Small.	Origin distant.
11	0 19 25 a.m.	*	110	23.6	0.011	0.028	
12	9 27 30 p.m.	Slight.	40	8.3	—	0.039	Accompanied by sound.
15	9 23 30 a.m.	*	60	?	—	Small.	Origin distant.
„	10 40 30 a.m.	*	140	69.0	—	0.011	
„	5 12 50 p.m.	*	100	?	—	0.009	Origin distant.
„	5 37 10 p.m.	*	100	?	—	Small.	Do.
16	7 47 21 a.m.	*	50	19.4	—	0.003	
„	9 02 51 a.m.	*	80	27.0	—	0.011	
17	9 37 10 p.m.	*	80	30.0	—	0.030	
18	1 08 48 a.m.	Slight.	90	9.0	0.008	0.053	Accompanied by sound.
„	10 51 38 a.m.	*	60	19.0	—	0.006	
20	0 47 40 a.m.	Slight.	10	2.5	—	0.022	Accompanied by loud sound. The diagram consisted almost only of a single stroke.
21	2 28 37 a.m.	*	40	?	—	0.002	
22	11 32 07 p.m.	*	90	35.0	—	0.006	Origin distant.

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Date.	Time of Occurrence.	Intensity.	Total Duration.	Duration of Prel. Tremor.	Max. Motion in		Remarks.
					Prel. Tremor.	Principal Portion.	
	August.						
	h m s		sec.	sec.	mm.	mm.	
23	2 03 42 p.m.	*	35	?	—	Small.	Origin distant.
„	11 45 57 p.m.	*	30	6.7	0.002	0.004	
24	1 33 55 a.m.	Slight.	55	13.3	0.003	0.031	
„	3 01 17 a.m.	*	40	?	—	0.003	Origin distant.
„	0 05 38 p.m.	Moderate.	75	6.3	0.044	0.780	Loud sound heard toward S.
25	6 49 10 p.m.	Slight.	235	99.0	0.061	0.097	Accompanied by sound.
26	3 52 10 p.m.	Do.	26	6.7	0.002	0.009	Do.
„	4 18 00 p.m.	*	30	?	—	Small.	Origin distant.
„	5 33 10 p.m.	*	30	?	—	Do.	Do.
27	3 40 56 p.m.	*	70	?	—	0.020	Origin distant.
28	4 10 00 a.m.	*	80	?	—	0.014	Do.
„	8 56 00 a.m.	*	40	?	—	0.002	Do.
29	1 27 30 a.m.	Slight.	60	8.4	—	0.028	Accompanied by sound.
„	3 04 28 a.m.	*	30	14.5	—	0.004	
„	1 23 57 p.m.	*	30	?	—	Small.	Origin distant.
„	7 51 54 p.m.	*	55	25.0	—	0.007	
„	7 55 35 p.m.	Slight.	40	9.6	—	0.018	
30	1 15 42 a.m.	*	30	7.9	—	0.009	
„	9 27 02 a.m.	*	40	23.0	—	Small.	
31	7 40 15 a.m.	*	40	9.7	—	0.006	
„	1 17 46 p.m.	Slight.	55	8.8	—	0.030	Accompanied by sound.
„	1 35 45 p.m.	*	50	12.5	—	0.017	
	September.						
1	9 39 44 a.m.	Slight.	95	40.0	—	0.022	Accompanied by sound.
„	11 48 30 a.m.	Moderate.	220	79.0	0.032	0.150	Sound heard toward S.
2	0 53 23 a.m.	*	120	36.0	—	0.013	

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Date.	Time of Occurrence.	Intensity.	Total Duration.	Duration of Prel. Tremor	Max. Motion in		Remarks.
					Prel. Tremor	Principal Portion	
	September.						
	h m s		sec.	sec.	mm.	mm.	
2	3 35 12 p.m.	*	20	?	—	Small.	Origin distant.
„	3 48 25 p.m.	*	110	34.3	0.002	0.017	
„	4 26 30 p.m.	Moderate.	90	13.1	0.006	0.094	Loud sound heard toward S.
„	7 05 10 p.m.	*	70	12.3	—	0.016	
3	2 03 20 a.m.	Moderate.	140	10.6	0.012	0.150	Sound heard toward S.
4	7 32 30 a.m.	Slight.	30	6.9	—	0.006	Accompanied by sound.
„	8 49 35 a.m.	Do.	70	9.2	0.003	0.044	Do.
6	1 02 00 a.m.	*	60	?	—	0.007	Origin distant.
8	0 01 12 a.m.	*	60	?	—	0.002	Do.
9	11 35 17 p.m.	*	40	?	—	0.010	Do.
10	4 54 21 a.m.	*	40	?	—	0.004	Do.
11	4 38 38 p.m.	*	90	30.0	—	0.010	
„	7 52 10 p.m.	*	30	?	—	Small.	Origin distant.
„	10 16 20 p.m.	*	20	?	—	Do.	Do.
12	10 03 45 a.m.	*	20	?	—	Do.	Do.
„	11 36 25 a.m.	*	—	8.3	—	0.002	
13	5 36 15 p.m.	Slight.	70	7.4	0.003	0.017	Accompanied by loud sound.
14	2 44 05 a.m.	Do.	25	6.8	0.003	0.022	Accompanied by sound.
„	8 36 50 p.m.	*	50	8.4	—	0.003	
15	1 21 25 a.m.	*	40	?	—	0.002	Origin distant.
„	2 13 35 p.m.	Slight.	50	12.0	0.002	0.022	Accompanied by sound.
16	6 35 30 a.m.	*	40	14.6	—	0.002	
17	3 54 01 a.m.	*	60	?	—	0.004	Origin distant.
„	4 34 43 a.m.	*	30	?	—	0.003	Do.
„	4 58 54 p.m.	*	40	17.6	—	0.004	
„	9 03 00 p.m.	*	80	32.3	—	0.003	
„	9 46 30 p.m.	*	30	9.3	—	Small.	

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Date.	Time of Occurrence.	Intensity.	Total Duration.	Duration of Prel. Tremor.	Max. Motion in		Remarks.
					Prel. Tremor.	Principal Portion.	
	September.						
	h m s		sec.	sec.	mm.	mm.	
18	10 17 20 a.m.	*	80	21.0	—	0.018	
„	9 01 45 p.m.	*	120	39.0	—	0.006	
19	10 48 00 a.m.	*	60	?	—	0.007	Origin distant.
„	10 36 30 p.m.	*	30	7.8	—	0.010	
20	4 22 10 p.m.	Slight.	65	8.4	0.002	0.038	Loud sound of some duration heard toward S.
21	9 58 40 p.m.	*	40	?	—	0.002	Origin distant.
„	10 00 55 p.m.	Moderate.	120	9.7	0.250	0.860	No sound.
22	11 45 30 a.m.	*	70	?	—	0.011	Origin distant.
„	6 07 25 p.m.	*	120	40.2	0.006	0.024	
23	3 34 10 a.m.	*	25	10.0	—	0.002	
„	3 42 25 a.m.	*	25	?	—	0.004	Origin distant.
„	11 21 30 a.m.	*	30	?	—	0.007	Do.
„	4 42 30 p.m.	*	25	?	—	0.002	Do.
24	2 08 40 a.m.	Moderate.	85	7.8	0.031	0.210	Sound heard toward SW.
25	9 16 28 p.m.	Slight.	Short.	0.0	—	0.022	Accompanied by sound.
26	3 25 36 p.m.	Do.	70	9.0	0.017	0.056	Loud sound heard toward SW.
27	9 47 28 p.m.	*	120	24.0	0.006	0.025	
29	7 22 00 p.m.	Slight.	25	5.8	0.002	0.007	Accompanied by sound.
30	8 44 55 p.m.	*	70	?	—	0.014	Origin distant.
	October.						
1	6 18 00 a.m.	Slight.	25	7.6	—	0.013	
2	7 47 10 a.m.	*	40	6.6	—	0.006	
„	10 56 20 a.m.	Moderate.	160	10.0	0.097	0.580	
3	2 53 45 a.m.	Slight.	35	10.6	—	0.002	
„	4 12 25 p.m.	Do.	35	3.6	—	0.036	Accompanied by loud sound.
„	7 50 46 p.m.	Do.	60	9.1	0.014	0.026	Do.

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Date.	Time of Occurrence.	Intensity.	Total Duration.	Duration of Prel. Tremor.	Max. Motion in Prel. Tremor.	Max. Motion in Principal Portion.	Remarks.
	October.						
	h m s		sec.	sec	mm.	mm.	
4	8 15 55 a.m.	*	Long.	—	—	—	Origin distant.
„	2 40 55 p.m.	Slight.	Short.	Short.	—	—	Accompanied by loud sound.
5	1 56 44 a.m.	*	60	14.7	—	0.017	
6	8 51 40 p.m.	Slight.	25	5.9	—	0.007	Accompanied by loud sound.
8	6 11 10 a.m.	*	50	18.0	—	0.002	
10	5 10 55 a.m.	*	180	88.0	0.007	0.017	
„	10 54 10 a.m.	Moderate.	145	9.2	0.061	0.430	Loud sound heard toward S.
„	11 10 55 a.m.	Slight.	30	P	—	0.020	
„	1 49 20 p.m.	Do.	60	P	—	0.039	Origin distant.
„	2 08 00 p.m.	Dp.	240	95.0	0.011	0.076	
„	2 28 20 p.m.	Do.	90	P	—	0.056	Origin distant.
„	2 36 10 p.m.	*	90	P	—	0.017	Do.
„	2 58 50 p.m.	*	120	P	—	0.020	Do.
„	3 22 10 p.m.	*	60	P	—	0.038	Do.
„	4 52 30 p.m.	*	40	P	—	Small.	Do.
„	8 51 15 p.m.	Slight.	90	39.0	—	0.038	Loud sound heard toward S.
„	9 34 35 p.m.	*	70	1.14	—	0.011	
„	9 46 40 p.m.	*	60	23.4	—	Small.	
11	9 18 05 a.m.	*	70	P	—	Do.	Origin distant.
„	3 43 18 p.m.	*	60	16.0	—	0.011	
12	8 06 00 a.m.	*	40	10.0	—	0.004	
13	9 27 15 p.m.	*	40	P	—	Small.	Origin distant.
14	11 54 20 a.m.	Moderate.	80	5.7	0.044	0.240	Accompanied by sound.
„	4 33 05 p.m.	Slight.	Short.	19.0	—	0.018	
15	6 46 35 a.m.	Do.	60	12.0	—	0.030	Accompanied by sound.
16	0 34 27 p.m.	*	60	15.1	—	0.011	
„	4 20 55 p.m.	*	60	P	—	Small.	Origin distant.

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Date.	Time of Occurrence.	Intensity.	Total Duration.	Duration of Prel. Tremor.	Max. Motion in Prel. Tremor.	Max. Motion in Principal Portion.	Remarks.
	October.						
	h m s		sec.	sec.	mm.	mm.	
17	1 21 00 p.m.	*	40	?	—	0.006	Origin distant.
„	4 52 10 p.m.	*	30	?	—	0.033	Do.
18	4 59 45 a.m.	*	40	?	—	0.003	Do.
„	5 00 50 a.m.	*	50	10.0	—	0.006	
„	5 04 55 a.m.	*	50	9.3	—	0.002	
„	9 54 05 p.m.	*	70	10.2	—	0.013	
19	9 10 20 a.m.	Moderate.	85	9.8	0.060	0.120	Accompanied by sound.
„	9 04 20 p.m.	*	50	?	—	0.004	Origin distant.
20	2 43 30 a.m.	*	60	?	—	0.017	Do.
„	1 42 10 p.m.	*	40	?	—	0.004	Do.
„	2 16 00 p.m.	*	90	43.0	—	0.011	
22	9 38 10 a.m.	*	75	?	—	0.018	Origin distant.
„	9 39 55 a.m.	*	60	?	—	0.018	Do.
„	11 42 30 a.m.	*	85	?	—	0.028	Do.
„	11 43 35 p.m.	*	60	14.4	—	0.031	
23	6 00 00 p.m.	*	40	8.9	—	0.012	
24	0 48 10 p.m.	Moderate.	180	50.0	0.008	0.058	
25	11 12 40 p.m.	*	100	?	—	0.004	Origin distant.
26	6 01 50 a.m.	*	90	?	—	0.003	Do.
27	1 29 25 a.m.	*	60	?	—	0.003	Origin distant.
28	6 47 15 p.m.	*	60	?	—	0.013	Do.
30	7 36 00 a.m.	*	60	8.3	0.006	0.013	
„	11 32 30 p.m.	*	60	?	—	0.003	Origin distant
31	1 02 40 p.m.	*	35	10.4	—	0.003	
	November.						
1	2 01 50 p.m.	Moderate.	180	?	—	0.140	No sound. Origin distant.

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Date.	Time of Occurrence.	Intensity.	Total Duration.	Duration of Prel. Tremor	Max. Motion in		Remarks.
					Prel. Tremor.	Principal Portion.	
	November.						
	h m s		sec.	sec.	mm.	mm.	
1	2 11 15 p.m.	Slight.	60	?	—	0.007	Accompanied by sound.
„	3 35 10 p.m.	*	70	?	—	0.007	Origin distant.
„	7 46 45 p.m.	Slight.	50	10.9	—	0.012	Accompanied by sound.
2	11 22 48 a.m.	Moderate.	110	12.9	0.073	0.190	No sound.
4	8 36 10 a.m.	Do.	80	11.4	0.019	0.120	Accompanied by sound.
5	2 12 40 a.m.	*	40	13.0	—	0.011	
„	3 32 50 p.m.	*	40	8.4	—	0.010	
8	11 11 20 p.m.	*	60	8.6	0.011	0.030	
9	5 56 00 a.m.	*	70	?	—	0.011	Origin distant.
„	7 10 50 p.m.	*	70	?	—	0.011	Do.
10	7 34 00 p.m.	Slight.	15	6.6	0.002	0.019	Accompanied by sound.
11	3 41 25 a.m.	*	60	19.7	—	0.018	
„	7 25 35 p.m.	Slight.	60	19.5	—	0.027	Accompanied by sound.
12	1 52 00 a.m.	Do.	80	10.6	0.007	0.071	Do.
„	8 53 10 a.m.	Do.	60	18.9	—	0.039	
16	10 28 30 p.m.	*	60	?	—	0.006	Origin distant.
19	0 49 50 a.m.	*	85	37.5	—	0.007	
„	2 51 24 a.m.	Slight.	50	4.5	0.003	0.044	Accompanied by loud sound.
„	6 08 05 p.m.	Do.	30	2.2	—	0.007	„ „ sound.
20	8 19 55 a.m.	*	45	16.0	—	0.007	
22	1 02 00 a.m.	*	25	—	—	—	
„	4 27 50 a.m.	*	60	—	—	—	
23	0 04 00 a.m.	*	30	—	—	—	
„	0 11 00 a.m.	*	120	50.0	—	—	
„	7 30 10 a.m.	*	85	—	—	—	
„	3 34 20 p.m.	*	80	—	—	—	
24	6 31 20 a.m.	Slight.	50	15.9	—	0.050	Accompanied by sound.

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Date.	Time of Occurrence.	Intensity.	Total Duration.	Duration of Prel. Tremor	Max. Motion in		Remarks.
					Prel. Tremor.	Principal Portion.	
	November.						
	h m s		sec.	sec.	mm.	mm.	
24	8 29 00 p.m.	Slight.	35	12.8	—	0.041	Accompanied by loud sound.
26	6 16 20 p.m.	Do.	70	11.1	0.006	0.044	„ „ sound.
27	0 34 10 p.m.	Do.	150	31.3	0.007	0.037	Do.
28	6 02 10 p.m.	Do.	40	8.3	—	0.018	Do.
29	8 05 10 a.m.	*	50	11.4	—	0.014	
„	11 45 55 p.m.	*	30	?	—	Small.	Origin distant.
30	10 31 00 p.m.	*	50	13.7	—	0.003	
	December.						
2	2 15 45 p.m.	Slight.	85	24.0	—	0.028	Accompanied by sound.
„	11 27 10 p.m.	*	55	9.9	—	0.016	
3	1 40 45 a.m.	*	60	9.8	—	0.020	
„	0 40 55 p.m.	Slight.	80	17.2	—	0.022	Accompanied by sound.
„	1 46 40 p.m.	Do.	140	29.0	0.014	0.061	
„	9 02 20 p.m.	Do.	30	6.2	—	0.003	Accompanied by sound.
5	1 07 10 a.m.	*	35	9.5	—	0.002	
„	1 20 40 a.m.	*	100	23.0	0.007	0.032	
„	4 38 45 a.m.	*	120	52.0	—	0.010	
6	10 20 10 p.m.	*	70	23.2	—	0.006	
„	11 09 40 p.m.	*	35	11.2	—	0.013	
7	6 39 10 a.m.	Slight.	80	7.1	—	0.049	Accompanied by sound.
„	6 47 55 a.m.	*	40	7.3	—	0.013	
8	11 40 15 a.m.	*	60	11.0	—	0.010	
9	8 14 50 p.m.	Slight.	45	8.1	0.003	0.013	Sound heard toward S.
11	5 29 10 a.m.	*	80	22.4	—	0.010	
„	11 06 15 a.m.	*	60	?	—	Small.	Origin distant.
„	11 39 25 a.m.	*	75	?	—	0.006	Do.

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Date.	Time of Occurrence.	Intensity.	Total Duration.	Duration of Prel. Tremor.	Max. Motion in		Remarks.
					Prel. Tremor.	Principal Portion.	
	December.						
	h m s		sec.	sec.	mm.	mm.	
11	2 41 20 p.m.	*	30	P	—	Small.	Origin distant.
12	5 01 45 a.m.	*	25	6.9	—	0.006	Sound only perceived.
14	5 48 30 p.m.	Slight.	50	8.4	—	0.016	Accompanied by sound.
16	11 25 36 a.m.	Do.	70	11.8	—	0.077	
,,	1 26 50 p.m.	*	80	15.8	—	0.006	
17	10 58 00 a.m.	Slight.	70	9.4	—	0.004	
,,	8 24 15 p.m.	*	50	8.0	—	0.011	
18	1 04 50 p.m.	*	Short.	Short.	—	Small.	Loud sound was perceived.
,,	7 56 00 p.m.	*	Do.	Do.	—	Do.	Do.
19	4 10 30 a.m.	*	80	P	—	0.004	Origin distant.
21	2 09 20 a.m.	Slight.	45	6.7	—	0.010	Accompanied by sound.
,,	5 20 30 a.m.	Do.	30	P	—	Small.	Origin distant.
,,	8 16 08 a.m.	Do.	100	8.0	—	0.033	
23	7 57 40 a.m.	*	60	14.1	—	0.007	
,,	11 38 05 a.m.	Moderate.	195	33.6	0.017	0.160	Accompanied by sound.
24	4 29 30 p.m.	*	50	17.5	—	0.010	
25	6 19 40 p.m.	Slight.	50	8.4	—	0.007	
,,	6 42 50 p.m.	Do.	80	9.2	—	0.033	
26	3 40 20 a.m.	*	10	—	—	—	
,,	6 45 00 a.m.	*	50	—	—	—	
,,	11 04 30 a.m.	Slight.	35	7.0	—	—	
,,	0 11 45 p.m.	Moderate.	240	12.0	—	0.188	Accompanied by sound.
,,	2 38 25 p.m.	*	20	—	—	—	
,,	7 10 20 p.m.	*	40	—	—	—	
27	0 50 50 p.m.	*	60	21.8	—	0.010	
,,	9 06 30 p.m.	*	50	P	—	0.007	
28	2 03 25 a.m.	*	40	P	—	0.008	Origin distant.

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Date.	Time of Occurrence.	Intensity.	Total Duration.	Duration of Prel. Tremor.	Max. Motion in		Remarks.
					Prel. Tremor.	Principal Portion.	
	December.						
	h m s		sec.	sec.	mm.	mm.	
28	4 08 40 p.m.	*	120	52.0	—	0.022	
29	6 59 30 p.m.	*	40	?	—	Small.	Origin distant.
„	7 02 40 p.m.	*	20	?	—	Do.	Do.
30	7 52 10 p.m.	*	80	9.6(?)	—	0.030	Do.

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Typical Diagrams. Typical diagrams are reproduced in Pls. I to V, as follows.

Plate.	Figure.	Date.	Time of Occurrence.	Intensity.	Remarks.
			Sharp Local Earthquakes.		
I	1	April 6	h m s 9 29 10 p.m.	Moderate.	Loud sound heard 5 or 6 sec. before the shock.
	2	July 27	1 38 15 a.m.	Do.	Accompanied by loud sound.
	3	June 11	11 50 10 p.m.	Do.	Do.
	4	„ 7	6 13 30 a.m.	Do.	Do.
	5	„ 27	3 17 10 a.m.	Slight.	Accompanied by sound.
			Large Earthquakes.		
II	6	September 21	10 00 55 p.m.	Moderate.	No sound.
	7	October 2	10 56 20 a.m.	Do.	Do.
			Small Local Shocks.		
III	8	September 2	4 26 30 p.m.	Moderate.	Accompanied by loud sound.
	9	April 6	11 33 40 p.m.	Unfelt.	
	10	May 26	2 00 25 a.m.	Slight.	Accompanied by sound.
	11	September 20	4 22 10 p.m.	Do.	„ loud sound.
	12	October 2	7 47 10 a.m.	Unfelt.	
	13	September 19	10 38 30 p.m.	Do.	
			Earthquakes of some Distant Origin. (*a*)		
IV	14	July 7	1 21 25 a.m.	Moderate.	No sound.
	15	November 1	2 01 50 p.m.	Do.	Do.
	16	June 12	5 17 30 p.m.	Do.	Sound heard 5 sec. before the shock.
	17	May 26	3 46 50 p.m.	Do.	Loud sound heard 3 sec. before the shock.
	18	October 10	1 49 20 p.m.	Slight.	

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Plate.	Figure.	Date.	Time of Occurrence.	Intensity.	Remarks.
		Earthquakes of some Distant Origin. (*b*)			
	19	July 7	h m s 7 17 25 a.m.	Moderate.	Accompanied by sound.
	20	August 25	6 49 10 p.m.	Slight.	Do.
	21	June 7	2 39 50 p.m. 2 40 20 „	Moderate. Slight.	Accompanied by loud sound.
V	22	July 7	10 33 00 a.m.	Unfelt.	
	23	October 10	5 10 55 a.m.	Do.	
	24	June 27	1 09 30 a.m.	Do.	
	25	September 2	3 48 25 p.m.	Do.	

The characteristics of a sharp local shock are the shortness of the duration of the preliminary tremor, and the occurrence of the maximum vibration of the latter and the principal portion at the commencement of each of the respective phases. In the cases of the four *moderate* earthquakes of April 6, July 27, and June 11 and 7, (Figs. 1 to 4, Pl. I), which were each accompanied or preceded by a loud sound, the duration of the preliminary tremor varied between 5.6 and 7.9 sec., the maximum double amplitude in the principal portion being 0.190 to 0.490 mm. In the *slight* earthquake of June 27 (Fig. 5, Pl. I), the duration of the preliminary tremor was 12.1 sec., the maximum motion being 0.183 mm.

The two earthquakes of Sept. 21 and Oct. 2, (Figs. 6 and 7, Pl. II), which were larger than those above mentioned were, according to the report of the observers, not accompanied by sound.

Of the six small local shocks whose diagrams are given in Pl. III, that on Sept. 2, (Fig. 8), was accompanied by loud sound and was moderate in intensity, although its maximum motion was only 0.094 mm; the preliminary tremor having lasted 13.1 sec.

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The *slight* earthquakes on May 26 and Sept. 20, (Figs. 10 and 11), were also accompanied by sound, which was loud in the case of the second shock. Of the remaining three insensible earthquakes, (Figs. 9, 12, and 13), those on Oct. 2 and Sept. 19 were extremely small.

Of the four *moderate* earthquakes (PL. VI), whose origins were at some distance from Tsukuba, those on July 7 and Nov. 1, (Figs. 14* and 15), are reported as having been accompanied by no sound. The other two shocks, which happened on June 12 and May 26, were each preceded by loud sound. The slight earthquake on Oct. 10 (Fig. 18) was similar to, but much smaller than, that on May 26 (Fig. 17).

The diagram of the earthquake of July 7 (Fig. 19), which was accompanied by sound, presents an appearance of two shocks happening in succession, the motion being comparatively large in the preliminary tremor, which was of a long duration and lasted 62 sec. In fact, this earthquake has been reported by the observers at Tsukuba as two distinct ones, whose intensities were *slight* and *moderate* respectively. The diagram of the earthquake of Aug. 25 (Fig. 20), indicates the similar peculiarity still more markedly; the motion in the preliminary tremor, which lasted 99 sec., being not much smaller than that in the principal portion. This earthquake was also reported as two separate ones, each of which was *slight* and was accompanied by sound. The latter circumstance is very interesting, as it gives support to the view that the earthquake sound occurs not only in the preliminary tremor, but also in the principal portion. The two unfelt earthquakes on July 7 and Oct. 10, (Figs. 22 and 23), are much similar in character to

* The zero-position of the recording pointer of the instrument suffered some displacement during the shaking.

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the two shocks above mentioned. Fig. 21 represents, on the other hand, a case of two really distinct earthquakes one of which was *moderate* and the other *slight*, happening in quick succession. Finally, the two earthquakes on June 27 and Sept. 2 are examples of shocks of somewhat distant origin, whose preliminary tremor is small.

Duration of the preliminary tremor. The relative frequencies of the different lengths of the duration of preliminary tremor less than 40 sec., measured in the cases of 329 earthquakes, were as shown in the following table

Duration of Prel. Tremor.	Number of Earthquakes.	Duration of Prel. Tremor.	Number of Earthquakes.
sec. sec.		sec. sec.	
0.0—0.9	9	20.0—20.9	3
1.0—1.9	0	21.0—21.9	3
2.0—2.9	2	22.0—22.9	4
3.0—3.9	2	23.0—23.9	6
4.0—4.9	4	24.0—24.9	3
5.0—5.9	15	25.0—25.9	4
6.0—6.9	29	26.0—26.9	0
7.0—7.9	24	27.0—27.9	1
8.0—8.9	36	28.0—28.9	2
9.0—9.9	35	29.0—29.9	3
10.0—10.9	21	30.0—30.9	5
11.0—11.9	18	31.0—31.9	1
12.0—12.9	13	32.0—32.9	3
13.0—13.9	11	33.0—33.9	1
14.0—14.9	11	34.0—34.9	1
15.0—15.9	8	35.0—35.9	3
16.0—16.9	9	36.0—36.9	3
17.0—17.9	11	37.0—37.9	2
18.0—18.9	9	38.0—38.9	0
19.0—19.9	12	39.0—39.9	2

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The number of cases, in which the duration of the preliminary tremor was over 40 sec., is 24, as follows:—

Duration of the Prel. Tremor.	
40 sec.	58 sec.
40.2	60
41	62
41	62
43	63
46	65
49.3	69
50	79
50	88
52	95
52	99
54	114

As graphically illustrated in Fig. 26, Pl. VI, the duration of the preliminary tremor most frequently occurring was between 6 and 10 sec., the number of the corresponding earthquakes being equivalent to the two-thirds of all the others. The relation between the duration of the preliminary tremor and the corresponding frequency of earthquakes will be of course different for different places of observation.

Number of sensible shocks. The total number of the sensible shocks was 171, while that of mere sounds (not accompanied by perceptible earth movement) was 12, as follows.

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Month.	Sensible and Insensible Eqkes.	Number of		
		Sensible Eqkes.	Mere Sounds.	Sensible Eqkes, accompanied by Sound.
I	24	12	2	10
II	31	17	5	18
III	24	14	0	13
IV	26	7	1	7
V	27	8	0	5
VI	50	15	0	14
VII	67	21	1	17
VIII	48	11	0	9
IX	49	15	0	14
X	57	18	0	9
XI	35	16	0	13
XII	49	17	3	12
Sum	487	171	12	141

Thus the number of the sensible earthquakes, (including the cases of mere sounds), was 183, so that such shocks occurred at Tsukuba on the average once nearly every two days. The number of the insensible shakings was 304.

Earthquake sounds. At Tsukuba, earthquake sounds are perceived very often, which may be likend to the noises of distant thunders or of a wagon passing over a wooden bridge, those like the rushing of winds being comparatively rare. The monthly numbers of the sensible shocks accompanied by sound, including the cases of sounds without sensible motion, are given in the last column of the above table. From the latter it will be seen that earthquake sounds occurred in 141 cases, or in 77% out of the 183 sensible shocks. It is possible that all of the latter, or nearly so,

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are found to be accompanied by more or less sound, when very attentively observed.

There were 27 cases, in which the direction of the sound was noted, as follows:—

Sound heard toward the South .....17 cases.
,, South-West ..... 9 ,,
,, South-East..... 1 ,,

The resultant, or mean, direction was thus South-West by South. That the sounds were perceived as coming from this quarter may be due to the fact that the lower part of the southern slope of the mountain, where the town of Tsukuba is situated, is horse-shoe shaped and opens in the same direction to the low plane.

In a majority of cases the sound was first perceived, followed immediately or a few seconds later by the tremblings of the ground, as in the following examples.

Eqke of May 26..... Duration of Prel. tremor=19.4 sec.
Sound heard 3 sec. before the shock.

Eqke of June 12..... Duration of Prel. tremor=18.4 sec.
Sound heard 5 sec. before the shock.

It is probable that the commencement of the sound is generally at the same instant as that of the preliminary tremor, whose earlier part may often be insensible while the sound is perceptible. This explanation can not, however, be applied to the following two cases, provided the report of the observers be accurate:—

Eqke of April 6..... Duration of Prel. tremor=6.7 sec.
Sound heard 5 or 6 sec. before the shock.

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Eqke of June 11..... { Duration of Prel. tremor=5.6 sec.
Sound heard 3 sec. before the shock.

In each of these two shocks, which were *moderate* in intensity, the motion at the commencement of the preliminary tremor was quite large and perfectly sudden. Hence it seems impossible that sound should be heard a few seconds prior to the arrival of the sensible motion, unless the vibrations of the ground giving rise to the sound phenomena form a sort of an *ultra* preliminary tremor and are so extremely minute that the seismograph used could give no visible trace. Such a supposition may not be entirely wrong, since there are cases of loud sounds hardly accompanied by any movement.

Earthquake sound and duration of preliminary tremor.

The numbers of sensible earthquakes and of those accompanied by sounds, for the different lengths of the preliminary tremor, are given in the following table.

Duration of Prel. Tremor.	Total Number of Sensible Earthquakes=e.	Eqkes accompanied by Sound*=s.	Ratio: $\frac{s}{e}$
(i) sec. 0—5.0 sec.	18	18	100 %
(ii) 5.1—10.0	77	66	86
(iii) 10.1—15.0	35	28	80
(iv) 15.1—20.0	20	16	80
(v) 20.1—25 0	5	4	80
(vi) >25.1	18	10	56
Sum: (i) to (v)	155	132	85

(* Including the cases of mere sound.)

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Thus it will be observed that the sensible earthquakes of near origin of the duration of the preliminary tremor under 5 sec., were invariably accompanied by sound. The percentage number of the more distant shocks remained practically constant for the duration of the preliminary tremor between 5 and 25 sec., varying only between 86 and 80%, with the mean value of 85%. Even for the earthquakes of the duration of the preliminary tremor over 25 sec., the sound was by no means uncommon, the frequency amounting to 56%.

Distant earthquakes accompanied by sounds. Among the 183 sensible earthquakes, there were ten, which were accompanied by sounds, and the duration of whose preliminary tremor was longer than 25 sec., as follows.

Date.	Intensity.	Duration of Prel. Tremor.	Maximum Motion.
		sec.	mm.
March 21	Slight.	36.0	0.020
June 10	Do.	36.4	0.042
July 7	Moderate.	62.0	0.173
Do. 9	Do.	29.3	0.150
August 25	Slight.	99.0	0.097
September 1	Do.	40.0	0.022
Do.	Moderate.	79.0	0.150
October 10	Slight.	39 0	0.038
November 27	Do.	31.3	0.037
December 23	Moderate.	33.6	0.160

In these 10 earthquakes, the duration of the preliminary tremor varied between 29.3 and 99.0 sec., which correspond respectively

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to the epicentral distances of about 250 and 760 km; the maximum (EW component) motion in the principal portion varying between 0.020 and 0.173 mm. It is probable that even an earthquake at an epicentral distance of 1,000 km is able, when of a sufficient intensity, to produce sound phenomena at Tsukuba or any other district composed of hard rocks.

Earthquakes accompanied by loud sound. There were 35 cases in which the shock was accompanied by loud sound. The elements of motion in these earthquakes, arranged according to the length of the duration of the preliminary tremor, were as in the following table; the maximum movements in the preliminary tremor and the principal portion being denoted by 2a′ and 2a respectively.

Date.		Duration of Prel. Tremor.	Intensity.	Max. Motion in Prel. Tremor =2a′	Max. Motion in Princ. Portion =2a
		sec.		mm.	mm.
Jan.	25	0.0	Unfelt	—	(No. motion indicated)
Feb.	7	0.0	Slight	—	0.072
Oct.	4	(short)	Do.	—	Small
„	18	(Do.)	Unfelt	—	Do.
„	„	(Do.)	Unfelt	—	Do.
Aug.	20	2.5	Slight	—	0.022
Oct.	3	3.6	Do.	—	0.036
Nov.	19	4.5	Do.	0.003	0.044
July	12	4.7	Unfelt	0.002	0.004
April	30	4.9	Slight	—	0.036
„	27	5.4	Do.	0.004	0.021
Jan.	5	5.6	Do.	0.004	0.027
June	11	5.6	Moderate	0.066	0.230

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Date.		Duration of Prel. Tremor.	Intensity.	Max. Motion in Prel. Tremor $=2a'$	Max. Motion in Princ. Portion $=2a$
		sec.		mm.	mm.
Oct.	6	5.9	Slight	—	0.007
June	7	6.1	Do.	0.032	0.190
July	26	6.2	Do.	0.016	0.073
Aug.	24	6.3	Moderate	0.044	0.770
April	6	6.7	Do.	0.093	0.490
July	29	6.9	Slight	—	0.060
June	6	7.0	Moderate	0.013	0.106
July	27	7.9	Do.	0 039	0.340
Sept.	13	7.4	Slight	0.003	0.017
„	20	8.4	Do.	0.002	0.038
April	13	9.0	Do.	0.018	0.064
Sept.	26	9.0	Do.	0.017	0.056
July	9	9.1	Do.	—	0.049
Oct.	3	9.1	Do.	0.014	0.026
„	10	9.2	Moderate	0.061	0.430
May	9	11.0	Do.	0.051	0.204
Nov.	24	12.8	Slight	—	0.041
Sept.	2	13.1	Moderate	0.006	0.094
June	26	13.3	Slight	0.008	0.039
„	7	17.7	Moderate	0.027	0.093
May	26	19.4	Do.	0.043	0.160
Oct.	10	39.0	Slight	—	0.038

Thus it will be seen that loud sounds occurred most frequently in the earthquakes, whose preliminary tremor lasted less than about 9 or 10 sec., corresponding to an epicentral distance of about 100 km. In three cases, the duration of the preliminary tremor was much longer, being from 17.7 to 39.0 sec. Again, of the 35

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earthquakes tabulated above, 10 were *moderate*, 21 were *slight*, and the remaining 4 were unfelt shocks; each of the last having a very short preliminary tremor or apparently none whatever. The maximum motion in the preliminary tremor (=2a′) varied between 0.002 and 0.093 mm, and that in the principal portion (=2a) between 0.004 and 0.770 mm.* It is thus seen that the intensity of motion is not a necessary factor in the production of the sound phenomena, although a violent earthquake will always be accompanied by a very loud sound.

Ratio of maximum motion in preliminary tremor to that in principal portion. The maximum movements in the preliminary tremor and principal portion of the 7 sharp local shocks, whose diagrams are given in Pls. I and II, were as follows.

Date.		Duration of Prel. Tremor.	Max. Motion in Prel. Tremor =2a′.	Max. Motion in Princ. Portion =2a.	Ratio: $\frac{2a}{2a'}$
		sec.	mm.	mm.	
April	6	6.7	0.093	0.490	5.3
July	27	7.9	0.039	0.340	8.7
June	11	5.6	0.066	0.220	3.3
,,	7	6.1	0.032	0.190	5.9
,,	27	12.1	0.028	0.183	6.5
Sept.	21	9.7	0.250	0.860	3.4
Oct.	2	10.0	0.097	0.580	6.0
			Mean		**5.6**

Thus the motion in the preliminary tremor increased generally

* Excepting a few cases in which the motion was immeasurably small.

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with the strength of the shaking and was on the average 1/5.6 of that in the principal portion. Hence it is likely that a violent destructive shock of near origin begins abruptly with quite large vibrations, so that its preliminary tremor may be much stronger than the principal portion of an ordinary earthquake.

In the following table, I give the 2a′ and 2a in the 19 earthquakes of moderate intensity, whose duration of the preliminary tremor was under 20 sec. and whose absolutely greatest motion (2a) was over 0.1 mm; the shocks being arranged according to the magnitude of the latter element of motion.

Date.		Duration of Prel. Tremor.	Max. Motion in Prel. Tremor $=2a'$.	Max. Motion in Princ. Portion $=2a$.	Ratio: $\frac{2a}{2a'}$
		sec.	mm.	mm.	
Aug.	24	6.3	0 044	0.780	17.7
Oct.	10	9.2	0.061	0.430	7.0
„	14	5.7	0.044	0.240	5.5
Jan.	26	11.0	0.028	0.220	7.9
Sept.	24	7.8	0.031	0.210	6.8
May	9	11.0	0.051	0.204	4.0
June	18	13.2	0.023	0.190	8.3
Nov.	2	12.9	0.073	0.190	2.6
June	12	18.4	0.054	0.190	3.5
			Mean		**7.0**
Feb.	17	14.1	0.027	0.180	6.7
March	4	9.0	0.022	0.170	7.7
May	26	19.4	0.043	0.160	3.7
April	24	9.0	0.017	0.153	9.0

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Date.		Duration of Prel. Tremor.	Max. Motion in Prel. Tremor $=2a'$	Max. Motion in Princ. Portion $=2a$	Ratio: $\frac{2a}{2a'}$
		sec.	mm.	mm.	
Sept.	3	10.6	0.012	0.150	12.5
Feb.	7	17.0	0.036	0.120	3.3
July	19	9.3	0.022	0.120	5.4
Oct.	19	9.8	0.060	0.120	2.0
July	23	19.0	0.031	0.107	3.4
June	6	7.0	0.013	0.106	8.1
			Mean		**6.2**

Dividing the 19 earthquakes tabulated above into two groups, of $2a>0.19$ mm and of $2a<0.18$ mm, the average values of the ratio $2a/2a'$ come out to be 7.0 and 6.2 respectively; the variation of this ratio with the 2a being apparently not significant. The mean value of this ratio deduced from the preceding tables is 6.3.

Finally, confining our attention to those sensible earthquakes, which were not accompanied by sound, the mean value of the ratio of $2a/2a'$ is found to be 5.7. This is not materially different from the mean value, namely, 7.0, of the corresponding quantity for those shocks accompanied by loud sound (page 35).

Least limit of sensible motion. In the sensible earthquakes, unaccompanied by sound, the maximum motion 2a was usually greater than 0.013 mm, there being only three cases in which it was less than this limit. With the earthquakes accompanied by sound, however, the limit of sensible motion was still lower, due probably to the predominance of quick vibrations in

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these shocks; there being 14 cases in which the maximum motion 2a was less than 0.01 mm, as follows:—

mm	Number of Eqkes.
2a = 0.010	3
2a = 0.009	1
2a = 0.008	2
2a = 0.007	5
2a = 0.006	1
2a = 0.004	1
2a = 0.003	1

Making an allowance for the possible error in the measurement of very small movements, and provisionally excluding the last three cases, we may take the double amplitude of **0.007** mm as the limit of sensible vibration, the EW component motion alone being taken into account. Assuming the corresponding NS component to be of an equal range, the resultant double amplitude of the sensible motion would be about **0.01** mm. This latter value is to be regarded as the lowest limit of the earthquake motion which is intense enough to be felt without instrumental aid by people living in wooden houses at a quiet rocky district, where the earth vibrations are rapid.

The result here obtained is in accordance with that relating to the small vibrations of the ground caused artificially by an oil engine, etc. (See my paper, A Horizotal Tremor Recorder, in the *Publications*, No. 18). For Tokyo, the intensity of the lowest limit of the sensible motion was found to be an acceleration of 17 mm per sec. per sec. This is to be regarded as defining the feeblest earthquake motion sensible to people living in a large city or some other place where there is much disturbances arising

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from traffic, the working of steam engines, dynamos, etc. (See the *Publications*, No. 11.)

Conclusion. One of the principal objects in making the seismographic observations at Tsukuba was the comparison of the results there obtained with those simultaneously obtained in Tokyo and Mito, to determine thereby the accurate positions of the origins of the different local shocks, and also the relation between the epicentral distance and the duration of the preliminary tremor for near earthquakes. Further discussions on the Tsukuba observations in these connections are reserved for a future occasion. The instrumental study of the minute vibrations giving rise to sound phenomena is of course very important.

Tokyo, March 1908.

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Earthquake Observation on Mount Tsukuba.

EW Component. Multiplication=90.

Time : 1 interval=1 minute.

Fig. 6.
Sept. 21: $10^h 00^m 55^s$ Pm.

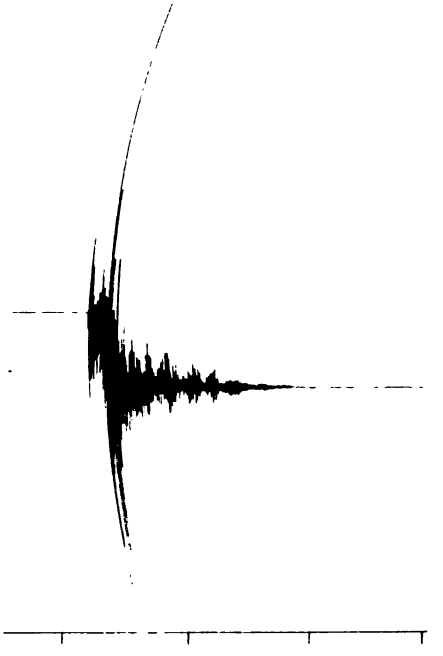

Fig. 7.
Oct. 2: $10^h 56^m 20^s$ Am.

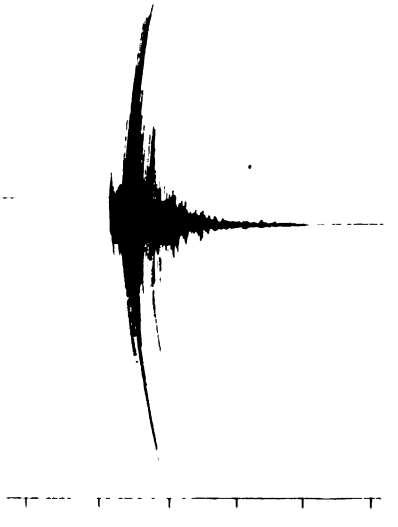

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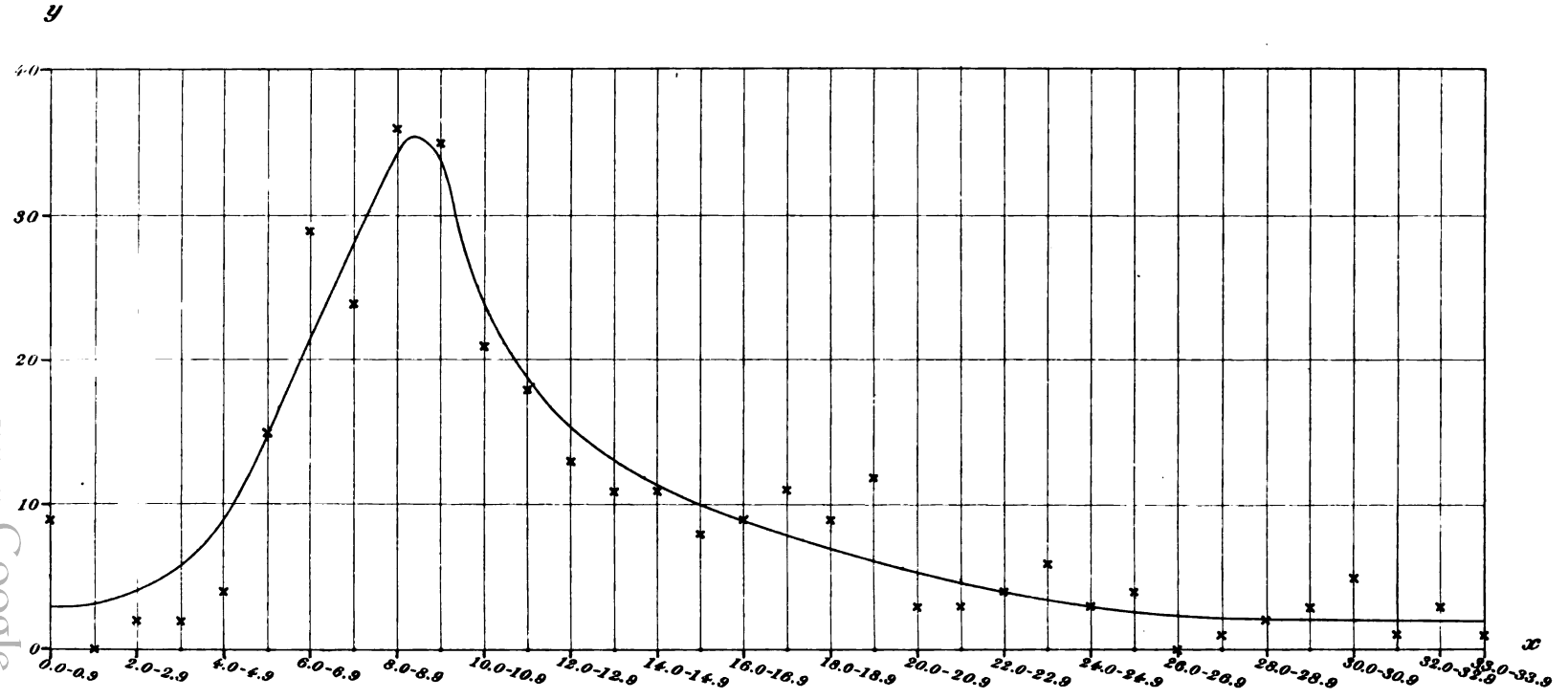
Fig. 26. Relative Frequencies of the Earthquakes of different lengths of the Duration of the Preliminary Tremor.

PL. VI.

x = Duration of the Preliminary Tremor, in second.

y = Number of the Earthquakes, the duration of whose preliminary tremor is equal to x.



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OF THE

Earthquake Investigation Committee

IN

FOREIGN LANGUAGES.

NO. 22 B. Art. 1-3.

TŌKYŌ, 1906.

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PUBLICATIONS OF THE EARTHQUAKE INVESTIGATION
COMMITTEE. NO. 22. SECTION B, ART I.

Strains produced by Surface Loading over a Circular Area with Applications to Seismology.

By

H. NAGAOKA, *Rigakuhakushi.*
Member of the Earthquake Investigation Committee.

With Plates I–III.

§ 1. The problem dealing with the strains of an isotropic elastic solid, bounded on one side by an infinite plane, was treated by Boussinesq and Cerruti. The former has published a series of researches on the allied subject in his treatise "Applications du Potentiel," in which full information of the problem in its varied aspects is to be obtained. A separate chapter is devoted to problems dealing with the strains produced by a vertical pressure applied over a circular area on the bounding horizontal plane, but unfortunately only a few particular cases of strains are worked out. Those who are interested in seismology may find it serviceable to have an approximate solution of the problem concerning the strain of the earth's crust, when there is surface loading, which may be likened to atmospheric pressure or to weight of rainfall exerted over a circular portion of the surface, in order to deduce the strains arising therefrom and thus obtain in some measure indications of the surface deformations due to the said natural agencies. With this object in view, interesting applications to seismology have already been made by Chree;* he discussed the influence of surface loading over a rectangular area and calculated the deviations

* Chree, Phil. Mag. **43**, 173, 1897.

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of the vertical and the tilting arising from it. A further extension of the problem to surface loading over a circular area is desirable, because the region of low or high pressure, as it is actually observed on the earth's surface, more resembles a circle than a rectangle. Moreover the loading is never uniform, so that the investigation of the problem or heterogeneous loading is not without interest. If the solution for an imperfect elastic solid, and for solids distributed in different strata were possible, the approximation to the actual problem as regards seismology would be of great value. The mathematical difficutly is however almost insurmountable, so that we are at present compelled to relinquish the attempt and satisfy ourselves with the solution for isotropic bodies.

Seismologists are familiar with the tremors associated with the change in the conditions of the atmosphere, sometimes in places quite outside the domain of low or high pressure. The question naturally arises how far from the place of surface loading the strain is appreciable, and how it depends on the extent of the stressed surface. Unfortunately the statical effect is generally difficult to observe, but the existence of the tremors itself indicates that the strain caused by the loading gives rise to elastic disturbance, calling forth free vibrations, which are presumably determined by the contour and geological structure of the region surrounding the place of observation. The surface wave thus called forth by distant surface loading is rather difficult of treatment, but we may obtain a crude idea from the calculation of the statical effect how far the influence of the stress is to be traced.

§ 2. Taking xy-coordinate plane as horizontal and z-axis vertically downwards, the components of elastic displacements u, v, w at point xyz in an isotropic elastic medium extending in positive direction of z axis, are given by

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$$(1)\begin{cases} u = -\dfrac{1}{4\pi\mu}\dfrac{\partial^2}{\partial x\partial z}\int r dP - \dfrac{1}{4\pi(\lambda+\mu)}\dfrac{\partial}{\partial x}\int \log(z+r)\,dP \\ v = -\dfrac{1}{4\pi\mu}\dfrac{\partial^2}{\partial y\partial z}\int r dP - \dfrac{1}{4\pi(\lambda+\mu)}\dfrac{\partial}{\partial y}\int \log(z+r)\,dP \\ w = -\dfrac{1}{4\pi\mu}\dfrac{\partial^2}{\partial z^2}\int r dP + \dfrac{2\lambda+3\mu}{4\pi\mu(\lambda+\mu)}\int \dfrac{dP}{r} \end{cases}$$

where λ, μ are Lamé's constants, and the integration with respect to pressure P at point x', y', o, extends over the stressed area. The radius vector r is given by

$$r^2 = (x-x')^2 + (y-y')^2 + z^2$$

Since

$$\frac{\partial^2 r}{\partial z^2} = \frac{1}{r} - \frac{z^2}{r^3},$$

the vertical displacement on the horizontal plane is given by

$$w_0 = \frac{\lambda+2\mu}{4\pi\mu(\lambda+\mu)}\int \frac{dP}{r} \tag{2}$$

and the horizontal displacement for loading over a circle amounts to

$$U = -\frac{1}{4\pi(\lambda+\mu)}\int \frac{1}{r}\frac{\partial r}{\partial a} dP \tag{3}$$

where $a^2 = x^2 + y^2$, the centre of the circle being taken for the coordnate origin.

§ 3. For the calculation of the strain due to stress over a circular area, we shall have to use the following notations.

R: radius of the circle.

a: distance of the centre of the circle from the point Q under consideration (x, y, o).

ρ: distance of surface point Q' $(x', y' o)$ from the centre of the circle.

r: radius vector from the point on the surface at which the strain is sought.

θ: angle between r and a.

φ: angle subtended by a at the point Q' (x', y', o).

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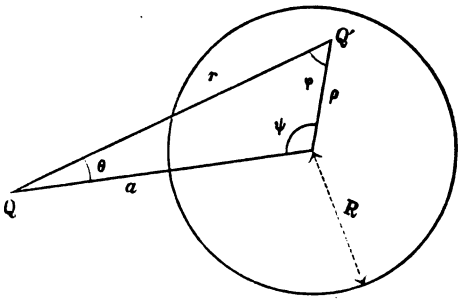
ψ: angle subtended by r at the centre.

The accompanying figure will show these quantities at a glance.



§ 4. Uniform Pressure over a Circular Area.

We have to consider the present problem in two aspects; (1) when the point Q under consideration is outside the stressed circle, (2) when the the point is inside the circle.

Let the pressure per unit area be denoted by p_0, then $dp=p\,\rho\,d\rho\,d\psi$, and since

$$r^2=a^2+\rho^2-2a\rho\cos\psi,$$

$$(4)\quad U=-\frac{1}{4\pi(\lambda+\mu)}\int\frac{1}{r}\frac{\partial r}{\partial a}dP=-\frac{p_0}{2\pi(\lambda+\mu)}\int_0^R\int_0^\pi\frac{(a-\rho\cos\psi)\rho d\rho d\psi}{a^2+\rho^2-2a\rho\cos\psi}$$

The integral

$$\int^\pi\frac{(a-\rho\cos\psi)d\psi}{a^2+\rho^2-2a\rho\cos\psi}=\frac{\pi}{2a}-\frac{\rho^2-a^2}{2a}\int_0^\pi\frac{d\psi}{a^2+\rho^2-2a\rho\cos\psi}$$

$$=\frac{\pi}{a}\quad\text{for}\quad a>\rho$$

$$=0\qquad,,\qquad a<\rho$$

Thus when the point Q lies inside the circle, we have to divide the integral into two parts

$$\int_0^R=\int_0^a+\int_a^R$$

of which the last part vanishes.

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Consequently we obtain

$$(5)\qquad \begin{cases} U=-\dfrac{p_0 R^2}{4(\lambda+\mu)a} & \text{for an } \textit{external} \text{ point} \\ U=-\dfrac{p_0 a}{4(\lambda+\mu)} & \text{,, ,, } \textit{internal} \text{ point.} \end{cases}$$

For positive pressure, the displacement tends towards the centre of the circle, and for negative pressure from it. For an external point, the horizontal displacement is directly proportional to the compressed area, and inversely proportional to the distance from the centre; for an internal point, it is simply proportional to the distance, so that the horizontal component is maximum at the periphery of the circle of pressure. Fig. 1. shows the graph of the displacement.

The vertical displacement is given by (2) in the form

$$(6)\qquad w_0=\frac{\lambda+2\mu}{4\pi\mu(\lambda+\mu)}\,p\iint dr d\theta$$

But $\rho^2=a^2+r^2-2ar\cos\theta$ and $\sin\theta=\dfrac{\rho}{a}\sin\varphi$, consequently

$$dr=\frac{\rho\,d\rho}{\sqrt{\rho^2-a^2\sin^2\theta}}$$

$$d\theta=\frac{\rho}{a}\,\frac{\cos\varphi}{\sqrt{1-\dfrac{\rho^2}{a^2}\sin^2\varphi}}\,d\varphi$$

Thus

$$(7)\qquad \frac{2\pi\mu(\lambda+\mu)}{\lambda+2\mu}\,w_0=\frac{p_0}{a}\int_0^R\int_0^\pi \frac{\rho\,d\rho\,d\varphi}{\sqrt{1-\dfrac{\rho^2}{a^2}\sin^2\varphi}} \quad \text{for an } \textit{external} \text{ point.}$$

At an internal point, we have to divide the circle into two concentric circles, such that the point Q lies on the periphery of the internal circle. The displacement w_0 consists of two parts w_0' and w_0'', of which

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$$(7_a)\qquad \begin{cases} \dfrac{2\pi\mu(\lambda+\mu)}{\lambda+2\mu} w_0' = \dfrac{p_0}{a}\displaystyle\int_0^a\int_0^\pi \frac{\rho\, d\rho\, d\varphi}{\sqrt{1-\dfrac{\rho^2}{a^2}\sin^2\varphi}} \\ \dfrac{2\pi\mu(\lambda+\mu)}{\lambda+2\mu} w_0'' = p_0\displaystyle\int_a^R\int_0^\pi \frac{d\rho\, d\varphi}{\sqrt{1-\dfrac{a^2}{\rho^2}\sin^2\varphi}} \end{cases}$$

and $w_0 = w_0' + w_0''$ for an *internal* point

To evaluate (7), let us put $\frac{\rho}{a} = \varkappa$, then

$$\int_0^R\int_0^{\frac{\pi}{2}} \frac{\rho\, d\rho\, d\varphi}{\sqrt{1-\dfrac{\rho^2}{a}\sin^2\varphi}} = \int_0^R K\rho\, d\rho = a^2\int_0^{\frac{R}{a}} K\varkappa\, d\varkappa$$

where K stands for a complete elliptic integral of the first kind. Using the wellknown formula

$$K\varkappa\, d\varkappa = d\left(\varkappa\varkappa'^2\frac{\partial K}{\partial \varkappa}\right)$$

$$\int_0^{\frac{R}{a}} K\varkappa\, d\varkappa = -k'^2K(k) + E(k)$$

where E in an elliptic integral of the second kind and $k = \frac{R}{a}$, $k' = \sqrt{1-\frac{R^2}{a^2}}$.

Thus

(8) $w_0 = \dfrac{\lambda+2\mu}{\pi\mu(\lambda+\mu)} p_0 a\{E(k) - k'^2K(k)\}$ for an external point.

On the periphery $\frac{R}{a} = 1$, and $E(1) = 1$; thus,

$$w_0 = \frac{\lambda+2\mu}{\pi\mu(\lambda+\mu)} p_0 a.$$

At an internal point

$$\frac{2\pi\mu(\lambda+\mu)}{\lambda+2\mu} w_0' = 2p_0 a$$

and

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$$\frac{2\pi\mu(\lambda+\mu)}{\lambda+2\mu}w''_0=p_0\int_0^{\pi}\int_a^R\frac{d}{d\rho}(\sqrt{\rho^2-a^2\sin\varphi})d\rho$$

$$=2p_0(RE(k)-a) \qquad \text{where} \quad k=\frac{a}{R}.$$

Thus

$$(8_a) \qquad w_0=\frac{\lambda+2\mu}{\pi\mu(\lambda+\mu)}p_0RE(k) \quad \text{for} \quad R>a.$$

The two expressions (8) and (8_a) coincide when $R=a$. The vertical displacement is greatest at the centre of the circle of pressure, and gradually decreases towards the periphery, but after passing out of the stressed area, the rate of diminution becomes extremely slow and ultimately vanishes in an asymptotic manner. Fig. 2 shows the amount of depression diagrammatically. These figures will bette- illustrate the general features of the horizontal and vertical displacer ments at a glance that a mere inspection of the mathematical formulas will show.

It may not be superfluous to give expressions for w_0 in terms of Weierstrass's notations. An easy calculation shows that

$$w_0=\frac{\lambda+2\mu}{\pi\mu(\lambda+\mu)}p_0\,a\frac{(\eta_1+e_2\omega_1)}{\sqrt{e_1-e_3}} \quad \text{where} \quad k=\frac{R}{a}$$

$$a\geqq R$$

$$w_0=\frac{\lambda+2\mu}{\pi\mu(\lambda+\mu)}p_0R\left(\frac{\eta_1+e_1\omega_1}{\sqrt{e_1-e_3}}\right) \quad \text{where} \quad k=\frac{a}{R}$$

$$R\geqq a$$

For the purposes of numerical calculation, it is convenient to have these expressions tranfsormed into ϑ-functions, in order that we may employ q-series with advantage.

Evidently

$$w_0=-\frac{2(\lambda+2\mu)}{\pi^2\mu(\lambda+\mu)}p_0a\vartheta_3(o)\vartheta''_3(o) \quad \text{for} \quad a\geqq R$$

and

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$$w_0 = -\frac{2(\lambda+2\mu)}{\pi^2\mu(\lambda+\mu)} p_0 R \frac{\vartheta''_2(0)}{\vartheta_2(0)\vartheta_3^2(0)} \quad \text{for} \quad a \leqq R.$$

both of which are easily expressed in terms of q.

Fig. 1.

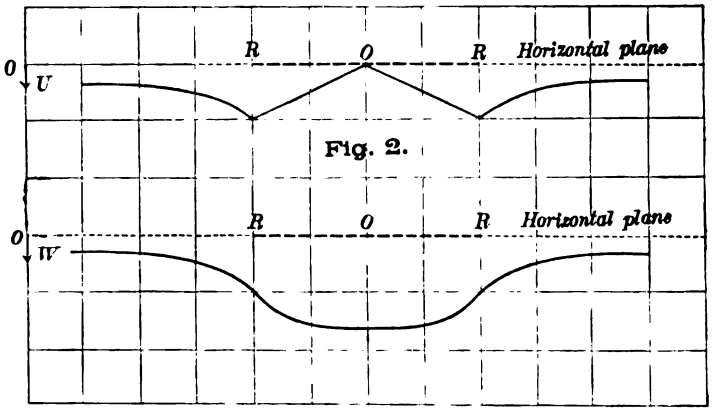

Fig. 2.

§ 5. Pressure over a Circular Area given by

$$p = P_0 - \rho^{2n}$$

In the present case we have to calculate

$$(9) \qquad \int_0^R \int_0^{\pi} \frac{(P_0-\rho^{2n})\rho d\rho d\varphi}{\sqrt{a^2-\rho^2\sin^2\varphi}}$$

for finding the vertical displacement at an external point.

For the sake of brevity, let us put

$$J_n = \int_0^R \frac{\rho^{2n+1}d\rho}{\sqrt{a^2-\rho^2\sin^2\phi}}$$

$a^2 = \alpha, \quad \sin^2\phi = \beta, \quad \rho^2 = x$;

then

$$J_n = \frac{1}{2}\int_0^{R^2} \frac{x^n dx}{\sqrt{\alpha+\beta x}}$$

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Putting $z^2=\alpha+\beta x$, we obtain

$$J_n=\int^{\alpha}\frac{\Delta(z^2-\alpha)^n}{\beta^{n+1}}dz \quad \text{where} \quad \Delta=\sqrt{1-\frac{k^2}{a^2}\sin^2\varphi}$$

which is easily integrable.

Let us consider two particular cases.

$n=1$:—

$$J_1=\frac{a^3}{\sin^4\varphi}\left(\frac{\Delta^3}{3}-\Delta+\frac{2}{3}\right)$$

$n=2$:—

$$J_2=\frac{a^5}{\sin^6\varphi}\left(\frac{\Delta^5}{5}-\frac{2\Delta^3}{4}+\Delta+\frac{8}{15}\right)$$

Putting $\int_0^{\varphi}\frac{d\varphi}{\Delta}=u$, we have

$$\Delta=dnu, \quad \sin\varphi=snu,$$

whence for

$$I_n=\int_0^{\frac{\pi}{2}}J_n d\varphi$$

we get

$$I_1=a^3\int_0^{K}\frac{1}{sn^4u}\left(\frac{dn^4u}{3}-dn^2u\right)du+\frac{2a^3}{3}\int_0^{\frac{\pi}{2}}\frac{d\varphi}{\sin^4\varphi}$$

$$I_2=a^5\int_0^{K}\frac{1}{sn^6u}\left(\frac{dn^6u}{5}-\frac{2dn^4u}{3}+dn^2u\right)du+\frac{8a^5}{15}\int_0^{\frac{\pi}{2}}\frac{d\varphi}{\sin^6\varphi}$$

The integrands can be easily reduced to the following forms.

$$\frac{1}{sn^4u}\left(\frac{dn^4u}{3}-dn^2u\right)=\frac{k^4}{3}+\frac{1}{3}\frac{k^2}{sn^2u}-\frac{2}{3sn^4u}$$

$$\frac{1}{sn^6u}\left(\frac{dn^6u}{5}-\frac{2}{3}dn^4u+dn^2u\right)=k^6-\frac{16}{15}\frac{k^4}{sn^2u}-\frac{4}{15}\frac{k^2}{sn^4u}+\frac{8}{15}\frac{}{sn^6u}$$

Using the formula of recursion

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$$sn^{2n-3}u\ cn\,u\,dn\,u=(2n-3)\int sn^{2n-4}u\,du-(2n-2)(1+k^2)\int sn^{2n-2}u\,du$$
$$+(2n-1)k^2\int sn^{2n}u\,du$$

we easily find

$$\int\frac{du}{sn^2u}=-\frac{cn\,u\,dn\,u}{sn\,u}+k^2\int sn^2u\,du$$

$$\int\frac{du}{sn^4u}=-\frac{cn\,u\,dn\,u}{3\,sn^3u}+\frac{2}{3}(1+k^2)\left(k^2\int sn^2u\,du-\frac{cn\,u\,dn\,u}{sn\,u}\right)-\frac{k^2u}{3}$$

$$\int\frac{du}{sn^6u}=-\frac{cn\,u\,dn\,u}{5\,sn^5u}+\frac{4}{3}(1+k^2)\int\frac{du}{sn^4u}-\frac{3}{5}k^2\int\frac{du}{sn^2u}$$

Remembering that at the limits

$u=0$	and	$u=K$
$dn(0)=1$		$dn(K)=k'$
$sn(0)=0$		$sn(K)=1$
$cn(0)=1$		$cn(K)=0$
$Z(0)=0$		$Z(K)=0$

we get

$$\int_0^K\left(\frac{k^4}{3}+\frac{k^2}{3sn^2u}-\frac{2}{3sn^4u}\right)du+\frac{2}{3}\int_0^{\frac{\pi}{2}}\frac{d\varphi}{\sin^4\varphi}=\frac{4(k^2-1)}{9}K+\frac{4+k^2}{9}E$$

After all the necessary reductions, we find that at points external to the circle, the vertical displacement of the horizontal plane amounts to

$$(10)\qquad w_0=\frac{2(\lambda+2\mu)}{9\pi\mu(\lambda+\mu)}\frac{p_0a^3}{R^2}\left\{2(1-2k'^2)E-k'^2(1-3k'^2)K\right\}$$

when the pressure distribution is given by

$$p=p_0(R^2-\rho^2)$$

In the interior of the circle, we have to calculate

$$\frac{2\pi\mu(\lambda+\mu)}{(\lambda+2\mu)p_0}w_0''=\int_a^R\int_0^{\frac{\pi}{2}}\frac{(R^2-\rho^2)\rho d\rho d\varphi}{\sqrt{\rho^2-a^2\sin^2\varphi}}$$

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$$= \frac{2R^3}{3}\int_0^K dn^4 u\,du - Ra + \frac{R^3k^2}{3} + \frac{2a^3}{9}$$

$$= \frac{2R^3\{2(1+k'^2)E - k'^2K\}}{9} - Ra^2 + \frac{5a^3}{9}$$

where $k^2 = \frac{a^2}{R^2}$, $k'^2 = \frac{R^2-a^2}{R^2}$

Add to this

$$\int_0^a\int_0^{\frac{\pi}{2}} \frac{(R^2-\rho^2)\rho\,d\rho\,d\varphi}{\sqrt{a^2-\rho^2\sin^2\varphi}} = Ra^2 - \frac{5a^3}{9}.$$

Consequently,

$$(10_a) \qquad w_0 = \frac{(\lambda+2\mu)p}{9\pi\mu(\lambda+\mu)} R\{2(1+k'^2)E - k'^2K^3\} \text{ where } k = \frac{a}{R}$$

and $R \geqq a$.

Thus at the centre of the circle, the depression amounts to

$$w_0 = \frac{\lambda+2\mu}{6\mu(\lambda+\mu)} R$$

and at the boundary

$$w_0 = \frac{2(\lambda+2\mu)}{9\pi\mu(\lambda+\mu)} R$$

As regards the horizontal displacement, we have for the law

$$p = p_0(R^2-\rho^2)$$

$$(11) \qquad U = -\frac{p_0 R_2}{8(\lambda+\mu)a} \qquad \text{for an } \textit{external} \text{ point}$$

and

$$(11_a) \qquad U = -\frac{p_0 a(2R^2-a^2)}{8(\lambda+\mu)R^2} \qquad \text{,, ,, } \textit{internal} \text{ point.}$$

The formulas (11) (11_a) show that the horizontal displacement for the pressure distribution $p = p_0(R^2-\rho^2)$ is somewhat similar to that already found for uniform pressure. The difference arises in the neighbourhood of the periphery $\rho = R$, where the maximum displacement is to be found. Fig. 3 gives the diagram of the horizontal displacement. As to the vertical displacement, and the complicated

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functions by which it is expressed is rather difficult to judge, but constructing a diagram (Fig. 4), we easily find that the depression is quite large at the centre, and the tilting is generally more uniform than for constant distribution of pressure. At distant points, the asymptotic approach to the horizontal plane is evident from the figures.

Fig. 3.

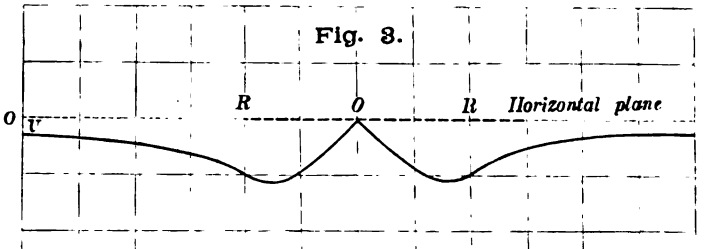
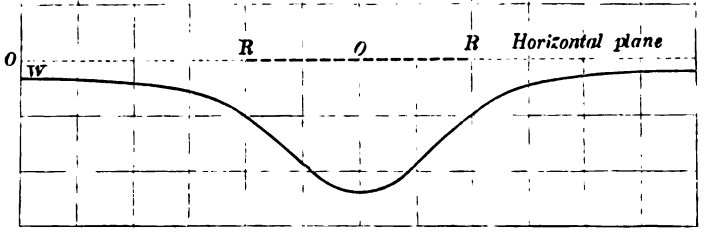


Fig. 4.



§ 6. Finally, let us find the depression in the vertical line through the centre. Evidently the sinking in depth z is given by

$$w_z = \frac{\lambda+2\mu}{4\pi\mu(\lambda+\mu)}\int\frac{dP}{r}+\frac{z^2}{4\pi\mu}\int\frac{dP}{r^3}$$

where $r^2=\rho^2+z^2$, x and y being put equal to zero. For uniform pressure p_0.

$$w_z = \frac{p_0(\lambda+2\mu)}{4\pi\mu(\lambda+\mu)}\int_0^R\int_0^{2\pi}\frac{\rho\,d\rho\,d\theta}{\sqrt{z^2+\rho^2}}+\frac{p_0 z^2}{4\pi\mu}\int_0^R\int_0^{2\pi}\frac{\rho\,d\rho\,d\theta}{(z^2+\rho^2)^{\frac{3}{2}}}$$

Putting $\frac{R}{z}=tg\,\alpha$, we get

$$w_z = \frac{p_0 R}{2\mu}tg\frac{\alpha}{2}\left(2\sin^2\frac{\alpha}{2}+\frac{\mu}{\lambda+\mu}\right) \tag{12}$$

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when the pressure distribution is given by $p=p_0(R^2-\rho^2)$

$$w_z=\frac{(\lambda+2\mu)p_0}{4\pi\mu(\lambda+\mu)}\int_0^R\int_0^{2\pi}\frac{(R^2-\rho^2)\rho\,d\rho\,d\theta}{R^2\sqrt{z^2+\rho^2}}+\frac{z^2}{4\pi\mu}\int_0^R\int_0^{2\pi}\frac{(R^2-\rho^2)\rho\,d\rho\,d\theta}{R^2(z^2+\rho^2)^{\frac{3}{2}}}$$

which by easy integration becomes

$$w_z=-\frac{p_0R}{4\eta}\frac{\sin\frac{\alpha}{2}}{\cos^3\frac{\alpha}{2}}\left\{\cos 2\alpha+\frac{(\lambda+2\mu)(1-3\cos^2\frac{\alpha}{2})}{3(\lambda+\mu)}\right\}. \tag{13}$$

These two formulas (12) and (13) show that the vertical depression in the central line of the stressed circle diminishes gradually, so that we may expect the effect to be felt at a considerable depth, provided the radius of the region of pressure is large. In the application to technical problems, R may be a small quantity, but in geophysical questions as regards the region of low pressure or of heavy rainfall, the result above arrived at will be of special interest. Fig.'s 5 and 6 show how the depression diminishes with the depth.

$R=$ Fig. 5.

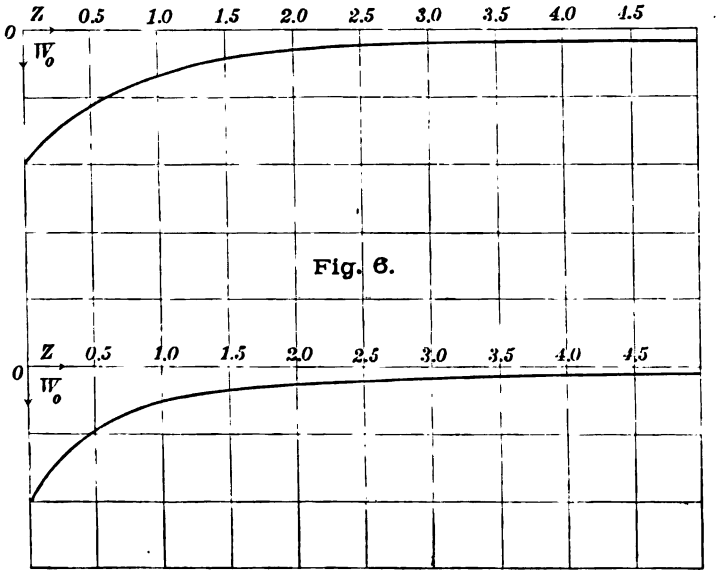

Fig. 6.

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§ 7. For the distributions of stress above considered, I have constructed the contour lines of equal depressions as shown in Fig.'s 7 and 8 Pl. I. From these diagrams, it is evident that the gradient of depression is greater near the periphery of the area of pressure. It is less marked for the case in which the pressure reaches a maximum value at the centre than for a uniform distribution.

When the depression due to pressures over two circular areas is to be found, we have to apply the principle of the superposition of small displacements. The effect can be most easily effected by using the same method of procedure as finding the equipotential lines by adding systems of such lines due to distinct sources. The depressions due to two positive or negative pressures over circular areas are represented in Fig. 9 and 10 *a*, *b*, *c*, Pl. II. These diagrams resemble the equipotential lines due to two attracting or repelling sources. When nagative pressure is exerted over one portion and positive pressure over the other, the lines of equal depression take the form given in Fig. 11 *a*, *b*, Pl. III.

§ 8. For those interested in seismology, it would not be out of place to state one or two instances of the amount of depression due to surface loading. Supposing the elastic medium to consist of andesite, we have to use the following elastic constants.*

$$\mu = 6 \times 10^{10} \text{ (C. G. S.)}$$

$$\frac{\mu(3\lambda+2\mu)}{\lambda+\mu} = \text{Young's modulus} = 8.80 \times 10^{10} \text{ (C. G. S.)}$$

When the pressure is uniform and $p_0 = 1$ cm. weight of mercury per cm^2, and $R = 50$ km., the depression at the periphery

$$w = 1.15 \text{ cm.}$$

and at the centre

$$w_0 = 1.80 \text{ cm.}$$

so that the mean tilting amounts to about 0″.02.

For $p = p_0(R^2 - \rho^2)$, and $p_0 R^2 = 1$ cm. weight of mercury

* H. Nagaoka. Pub. Earthq. Inv. Comm., No. 4, p. 60.

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$w_0 = 0.52$ cm. at the periphery
$w_0 = 1.23$ cm. „ „ centre

and the mean tilting is about 0.″02 as before. The elastic constants of the surface soil are evidently several times weaker than the andesite, so that the barometric change or rainfall might produce effects which would be within the limit of observation. With elastic solid of high plasticity, and with continuous application of pressure, there will be gradual increase of the strain, so that the effect may sometimes accumulate and at last attain an appreciable amount.

What will interest the seismologist in the present problem is the extent to which the strain due to vertical pressure is appreciable. If the area of pressure be confined to a small portion of the surface, the horizontal and the vertical components will practically vanish in its immediate neighbourhood, but the strained area increases almost in the same proportion as the stressed region, so that in the actual problem of the barometric change or of heavy rainfall, the effect would also be felt in places apparently remote from the place subjected to differences of surface pressure. The evanescence of the strain takes place almost asymptotically as already shown in the diagram, so that it will slightly disturb the elastic equilibrium and call forth vibrations or tremors. The surface wave which is most likely to be excited on the horizontal boundary and which is easily accessible to observation forms the next subject of discussion. Another problem, which will be interesting for seismology and volcanology is the strain on the horizontal surface, produced by internal pressure, a subject which I hope to be able to discuss in the near future.

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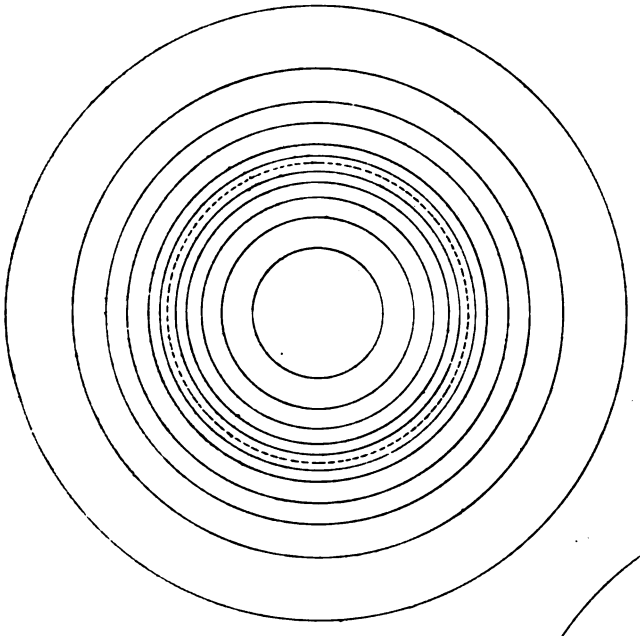
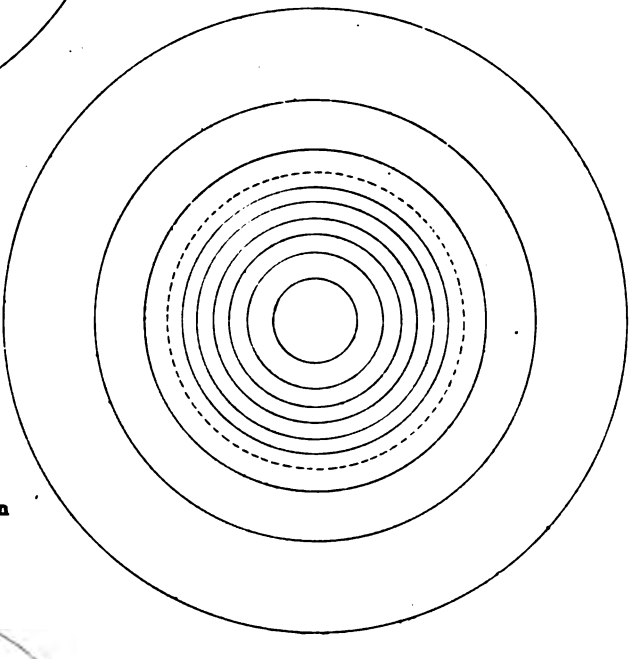
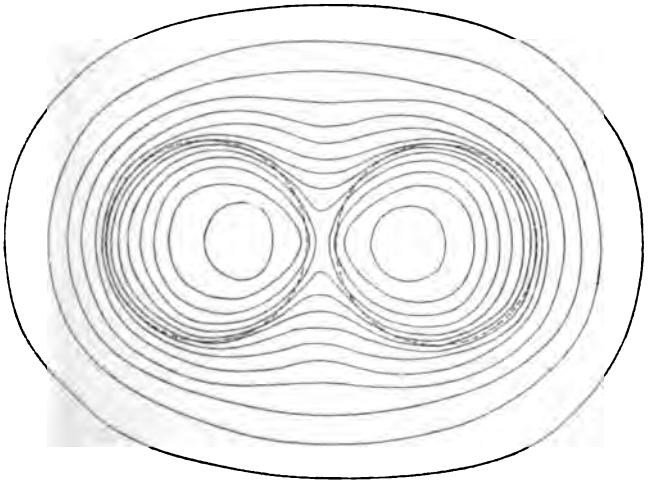
Depression due to $p=p_0$. (Fig. 7.)



Depression due to $p=p_0(R^2-\rho^2)$ (Fig. 8.)



Depression due to symmetrical distribution of pressure $p=p_0$. (Fig. 9.)



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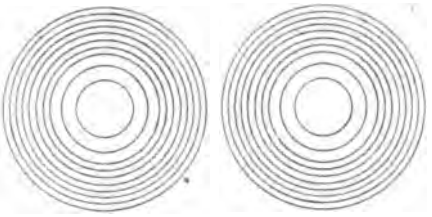
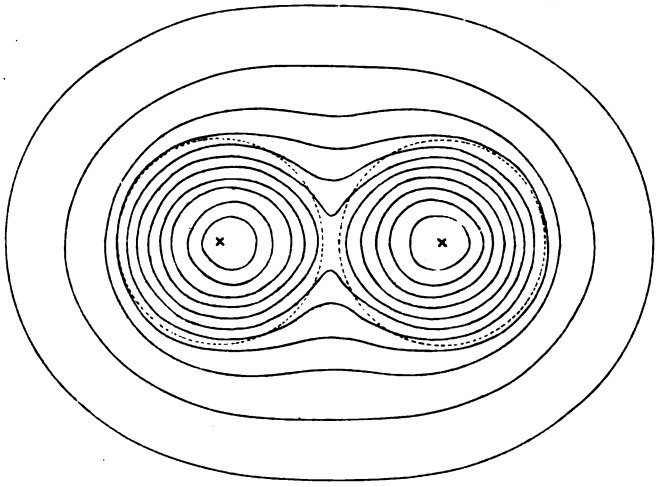
Pressure distribution. (Fig. 10a)



Depression due to symmetrical distribution of pressure $= p_0(K^2 - \rho^2)$

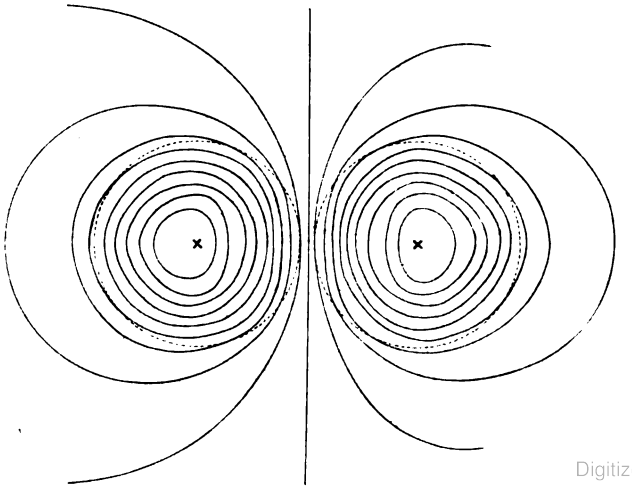
(Fig. 10b)



$p = p_0(K^2 - \rho^2)$

Elevation due to $p = -p_0(K^2 - \rho^2)$ Depression due to $p = p_0(K^2 - \rho^2)$

(Fig. 10c)



$p = -p_0(K^2 - \rho^2)$ $p = p_0(K^2 - \rho^2)$

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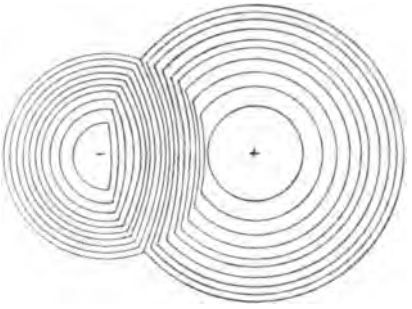
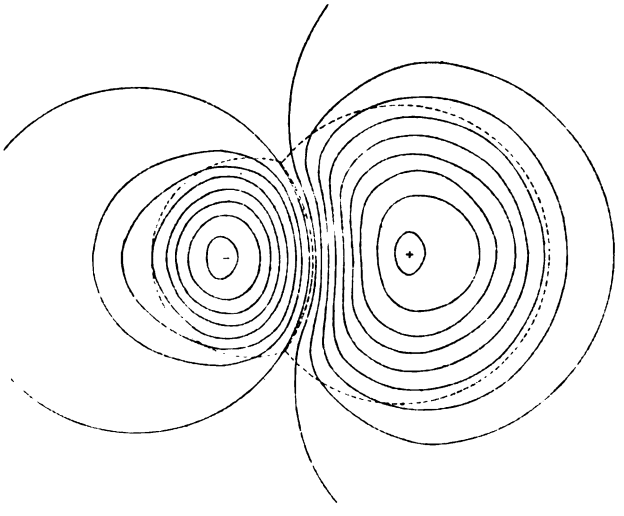
(Fig. 11_a)



Distribution of pressure

(Fig. 11_b)



Depression due to unsymmetrical distribution of pressure.

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PUBLICATIONS OF THE EARTHQUAKE INVESTIGATION
COMMITTEE. NO. 22. SECTION B, ART. 2.

Stationary Surface Tremors

By

H. NAGAOKA, *Rigakuhakushi.*

Member of the Earthquake Investigation Committee

With Plates I.

§ 1. The problem of elastic surface waves on an isotropic solid was first treated by Lord Rayleigh* in a paper communicated to the London Mathematical Society in 1885. The important bearing of this class of waves on earthquakes was recognised by him, but the result of analysis in its practical aspect has scarcely been discussed, inasmuch as the hypothesis of isotropy of the medium is hardly compatible with the structure of the earth's crust. When the great complexity which will be introduced into the boundary conditions if the stratigraphical structure such as is actually met with is taken into account, the advantage gained does not easily compensate for the mathematical difficulty which necessarily accrues in the solution of the problem. But if the result of calculation based on a simple abstraction as to the nature of the medium be interpreted in the light of a simple comment as to the character of the motion which is capable of being excited on the surface of the elastic solid, the analysis would not be a useless piece of mathematical play, as the conception of the phenomena is thereby greatly facilitated. A mere quantitative discrepancy will not prove imperfection of the theory, but one notices at a glance that the hypothesis made at the outset of calculation necessarily deviates from what is found in nature, where the intricacy and heterogeneity far surpass the power of modern analysis. The greatest objec-

* Lord Rayleigh, Proc. London Mathem. Soc., Vol 17, 4. 1887.

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tion which can perhaps be raised against the present treatment of the problem is the neglect of the influence of gravity in modifying the surface wave.

§ 2. Take the xy-plane at the horizontal boundary, and z-axis vertically downwards, and denote the component displacements by u, v, w; then the equations of motion becomes.

$$\rho\frac{\partial^2 u}{\partial t^2}=(\lambda+\mu)\frac{\partial\theta}{\partial x}+\mu\Delta\theta \tag{1}$$

with similar equations for v and w. Here ρ denotes the density, λ, μ Lamé's constants, and

$$\theta=\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}$$

$$\Delta\theta=\frac{\partial^2\theta}{\partial x^2}+\frac{\partial^2\theta}{\partial y^2}+\frac{\partial^2\theta}{\partial z^2}$$

For the free vibration of period $\frac{2\pi}{p}$, the equations can be easily reduced to the form

$$\begin{cases}(\Delta+k^2)\,u=\left(1-\dfrac{k^2}{h^2}\right)\dfrac{\partial\theta}{\partial x}\\ (\Delta+k^2)\,v=\left(1-\dfrac{k^2}{h^2}\right)\dfrac{\partial\theta}{\partial y}\\ (\Delta+k^2)\,w=\left(1-\dfrac{k^2}{h^2}\right)\dfrac{\partial\theta}{\partial y}\end{cases} \tag{2}$$

where

$$\begin{cases}h^2=\dfrac{\rho}{\lambda+\mu}p^2\\ k^2=\dfrac{\rho}{\mu}p^2\end{cases} \tag{3}$$

The equations can therefore be satisfied by

$$\begin{cases}u=-\dfrac{1}{h^2}\dfrac{\partial\theta}{\partial x}\\ v=-\dfrac{1}{h^2}\dfrac{\partial\theta}{\partial y}\\ w=-\dfrac{1}{h^2}\dfrac{\partial\theta}{\partial z}\end{cases} \tag{4}$$

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to which we shall have to add the complementary solutions satisfying

$$(5) \qquad (\Delta+k^2)u=0, \quad (\Delta+k^2)v=0, \quad (\Delta+k^2)w=0.$$

with the condition

$$\theta=\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0.$$

For the surface wave on the plane $z=0$, the displacements are proportional to

$$e^{i(fx+gy+pt)}$$

where f, g are constants to be determined by the boundary conditions.

By differentiating (4) with respect to x, y, z, we find

$$(6) \qquad (\Delta+k^2)\theta=0.$$

or

$$(6') \qquad \frac{\partial^2\theta}{\partial z^2}-(f^2+g^2-k^2\theta)=0.$$

Thus $\theta=Pe^{-rz}$ where $r^2=f^2+g^2-k^2$

The equation (5) can be written

$$(7) \qquad \frac{\partial^2 u}{\partial z^2}-(f^2+g^2-k^2)u=0.$$

or $u=Ae^{-sz}$ where $s^2=f^2+g^2-k^2$

Thus (4) and (5) give for u, v, w

$$(8) \qquad \begin{cases} u=-\dfrac{if}{k^2}Pe^{-rz}+Ae^{-sz} \\ v=-\dfrac{if}{k^2}Pe^{-rz}+Be^{-sz} \\ w=-\dfrac{r}{k^2}Pe^{-rz}+Ce^{-sz} \end{cases}$$

where P, A, B, C are all proportional to $e^{i(fx+gy+pt)}$ and A, B, C are connected by the relation

$$(8') \qquad i(fA+gB)-sC=0$$

which is equivalent to $\theta=0$. in the complementary term.

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The absence of shear at the horizontal boundary $z=0$ leads to the relation

$$(s^2+f^2+g^2)h^2C+2r(f^2+g^2)P=0, \tag{9}$$

while the evanescence of the normal surface traction is expressed by

$$(k^2-2h^2)P-2(r^2+sh^2C)=0. \tag{10}$$

Eliminating C and P between (9) and (10), we obtain

$$\{2(f^2+g^2)-k^2\}^4=16(f^2+g^2)^2(f^2+g^2-h^2)(f^2+g^2-k^2) \tag{11}$$

Remembering that

$$\frac{h^2}{k^2}=\frac{\mu}{\lambda+2\mu},$$

and putting

$$\gamma^2=\frac{k^2}{f^2+g^2}=\frac{\rho}{\mu(f^2+g^2)}p^2$$

we arrive at the equation

$$\gamma^6-8\gamma^4+24\gamma^2-16-16\left(\frac{\mu}{\lambda+2\mu}\right)(\gamma^2-1)=0. \tag{12}$$

for finding the frequency p of the free vibration, as given by Rayleigh.

The following real roots of γ have been calculated for different values of $\frac{\mu}{\lambda+2\mu}$ (with corresponding ratio σ of lateral contraction to longitudinal elongation).

$\frac{h^2}{k^2}=\frac{\mu}{\lambda+2\mu}$	σ	$\gamma=\frac{k}{\sqrt{f^2+g^2}}$
.0	$\frac{1}{2}$	0.9554
.1	$\frac{4}{9}$	0.9482
.2	$\frac{3}{8}$	0.9387
.3	$\frac{2}{7}$	0.9251

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.4	$\frac{1}{6}$	0.9052
.5	0	0 8741
.6	$-\frac{1}{4}$	0.8237

γ being determined for a given boundary, the displacements u, v, w are given by

$$(13)\qquad \begin{cases} u=\alpha\dfrac{if}{h^2}\left\{e^{-rz}+\dfrac{2rs}{s^2+f^2+g^2}e^{-sz}\right\}e^{i(pt+fx+gy)} \\ v=\alpha\dfrac{ig}{h^2}\left\{e^{-rz}+\dfrac{2rs}{s^2+f^2+g^2}e^{-sz}\right\}e^{i(pt+fx+gy)} \\ w=\alpha\dfrac{r}{h^2}\left\{e^{-rz}-\dfrac{2(f^2+g^2)}{s^2+f^2+g^2}e^{-sz}\right\}e^{i(pt+fx+gy)} \end{cases}$$

α being a constant to be found from the initial condition.

When there are several values of u_n, v_n, w_n, for u, v, w corresponding to different values of f and g, and consequently p, the displacements will be given by

$$(14)\qquad u=\Sigma u_n,\ v=\Sigma v_n,\ w=\Sigma w_n.$$

§ 3. When the elastic solid is bounded by two parallel planes, the discussion of waves can be generally reduced to that in two dimensions. If the bounding planes be given by

$$x=0,\ x=a,\ \text{and}\ z=0,$$

the surface wave would be generally given by the components u and w only.

Three different cases are to be distinguished.

(I) When both planes $x=0$, $x=a$ are clamped; then u varies as $\sin fx$ and

$$f=\frac{n\pi}{a},$$

consequently

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(15) $$p_n=r\frac{n\pi}{a}\sqrt{\frac{\mu}{\rho}} \qquad (n=1,\ 2,\ 3,\ \ldots.)$$

and the complete period is given by

(15′) $$T_n=\frac{2\pi}{p_n}=\frac{2a}{nr\sqrt{\frac{\mu}{\rho}}}$$

Writing $$a\frac{f}{h^2}\left(-e^{-rz}+\frac{2rs}{s^2+f^2}e^{-sz}\right)=A_n$$

$$a\frac{r}{h^2}\left(e^{-rz}-\frac{2f^2}{s^2+f^2}e^{-sz}\right)=C_n$$

where r, s are expressed by the above value of f,

(16) $$\begin{cases} u_n=A_n\begin{matrix}\cos\\ \sin\end{matrix} p_nt\ \sin n\pi\dfrac{x}{a} \\ w_n=C_n\begin{matrix}\sin\\ \cos\end{matrix} p_nt\ \sin n\pi\dfrac{x}{a} \end{cases}$$

satisfy the specified condition, so that the sum of these expressions will also represent the possible forms of surface waves.

II. When one boundary is clamped and the other is free,

$$u=0 \quad \text{for} \quad x=0$$

and $$\frac{\partial u}{\partial x}=0 \quad ,, \quad x=a.$$

Thus

$$u \propto \sin fx$$

where

(17) $$f=\frac{2n+1}{2}\frac{\pi}{a} \qquad (n=0,\ 1,\ 2,\ 3,\ldots\ldots)$$

and $$p_n=\frac{2n+1}{2}\frac{\pi}{a}r\sqrt{\frac{\mu}{\rho}}$$

or $$T_n=\frac{4}{2n+1}\frac{a}{r\sqrt{\frac{\mu}{\rho}}}$$

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The displacements are given by

$$(18)\qquad \begin{cases} u_n = A_n' \begin{matrix}\cos\\ \sin\end{matrix} p_n t \sin\left(\frac{2n+1}{2}\right)\frac{\pi x}{a} \\ w_n = C_n' \begin{matrix}\sin\\ \cos\end{matrix} p_n t \sin\left(\frac{2n+1}{2}\right)\frac{\pi x}{a} \end{cases}$$

III. When both planes $x=0$, $x=a$ are free,

$$\frac{\partial u}{\partial x}=0 \quad \text{for} \quad \begin{matrix} x=0 \\ x=a \end{matrix}$$

and $$u \propto \cos fx.$$

Evidently

$$(19)\qquad f=\frac{n\pi}{a} \qquad (n=1,\ 2,\ 3, \ldots\ldots)$$

and $$p_n=\frac{n\pi}{a}\gamma\sqrt{\frac{\mu}{\rho}}$$

or $$T_n=\frac{2a}{n\gamma\sqrt{\frac{\mu}{\rho}}}$$

which is the same as for clamped boundaries.

Consequently

$$(20)\qquad \begin{cases} u_n = A_n \begin{matrix}\sin\\ \cos\end{matrix} p_n t \cos\frac{n\pi}{a}x. \\ w_n = C_n \begin{matrix}\cos\\ \sin\end{matrix} p_n t \cos\frac{n\pi}{a}x. \end{cases}$$

§ 4. The case which is really worth consideration is when the boundary is yielding to a certain amount. As the surface soil is characterised by its plasticity, and the unevenness of the bounding surface makes the approach to the ideal case somewhat difficult, the general discussion of the yielding boundary in its application to geophysics may with propriety be postponed till the main cause of the surface tremors is well settled by observation. If we allow for the deviations in the actual case from what is assumed in the above discussion, the first case would correspond to the vibrations of a plain

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between parallel mountain ranges, the second case to those of a plain isolated by a ridge on one side and a mountain range on the other, and the third case to those of a high plateau or of a plain between two parallel rivers.

To give a numerical instance, let us suppose that $a=10$ km. $\sqrt{\frac{\mu}{\rho}}=3\frac{\text{km}}{\text{sec}}$, $\gamma=0.9$, then

$$\begin{cases} T_1 = 7.4 & \text{for (I) and (III)} \\ T_2 = 3.7 & \end{cases}$$

and

$$\begin{cases} T_0 = 14.8 & \text{,, (II).} \\ T_1 = 4.9 & \end{cases}$$

The above result shows that the vibration is quite analogous to the longitudinal vibration of rods; the nodes and loops are to be found in places which are aliquot parts of the breadth. The velocity of propagation is not so simply defined as in the case of rods.

The velocity of transversal wave $\sqrt{\frac{\mu}{\rho}}$ is perhaps very small for the uppermost strata of the earth's crust and probably much less than $3\frac{\text{km}}{\text{sec}}$. When the plain on which the surface wave is excited is of considerable extent, the period of stationary wave may attain a tolerably large value. If such motion be stimulated by progressive seismic waves, there is every possibility of the motion being traced on seismographs. One great drawback in seismometers is the impossibility of the discrimination of the progressive from the stationary waves. I am not aware if such waves have ever been observed, but it would not be out of place here to notice the probable appearance of vibrations of long periods.

The tremors accompanying the barometric change generally indicate persistence of surface waves for some intervals of time. As the surface soil is strongly damped, the evanescence will be quick; but the surface pressure is generally accompanied with strains, as already shown in the preceding paper, in regions quite remote from the place of actual application. The extent to which the horizontal component of the surface strain is felt is

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linearly related to the radius of the circular region subjected to stress. As is often met with on the earth's surface, the region of low pressure or of strong rainfall is not limited to a narrow space, but extends over hundreds or sometimes thousands of kilometres; the consequence is that the region in which the surface wave is liable to be excited is of vast extent. In countries which abound with mountains, interspersed with plains between, the surface waves may be either propagating or stationary, so long as the disturbing force is acting, whether the point under consideration be within the pressure domain or outside it.

The inspection of the diagram of tremors at once indicate the existence of beats in the vibrations. These are of exactly the same nature as is observed in the sea waves on calm days, where the bottom is irregular. These beats are probably due to the superposition of two vibrations of nearly equal periods and amplitudes. In the case of earth tremors, the existence of two such vibrations is to be traced to the nonuniformity of the surface strata, when either the elastic constants or the thickness of the horizontal strata are slightly different, there will be superposition of two waves giving rise to beats analogous to those well-known in light and sound.

§ 6. The fulfilment of the boundary condition in the present problem offers insurmountable difficulty to exact calculation, except for those boundaries which are conformable to rectangular coordinates or circles. The result of calculation in its practical application is only a rough approximation, and probably represents a part of the phenomena of earth tremors in its broadest aspect. The discussion of the present problem with special analogies to sea waves will not fail to be of special interest to those pursuing the study of geophysics, as there are so many points of resemblance between the two. I have therefore thought it advisable to give a diagram of sea waves observed at Odawara on a calm day, to show the close kinematical analogies which may exist between these two phenomena.

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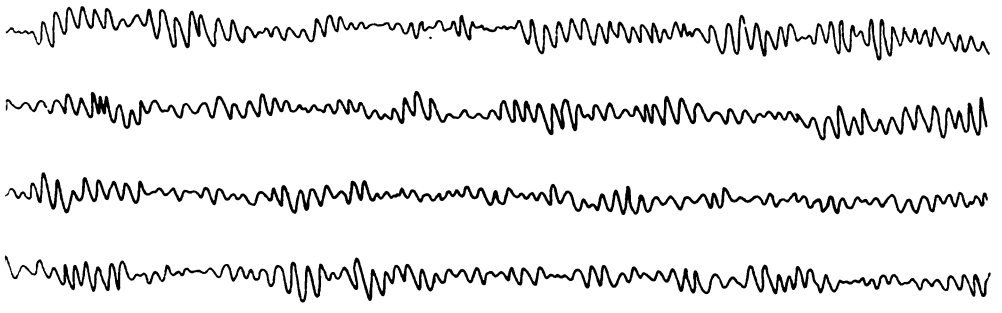

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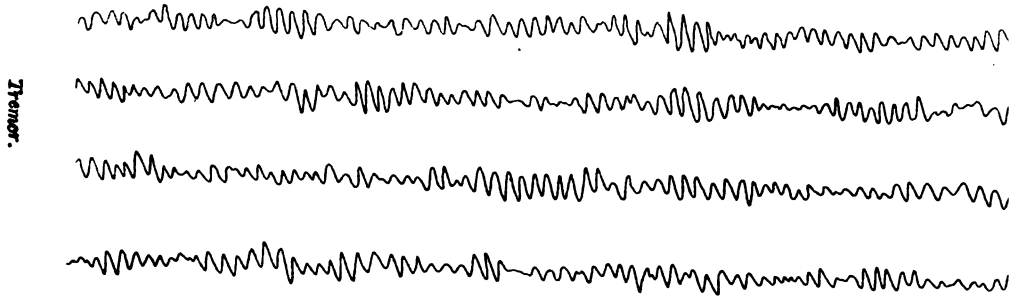

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PUBLICATIONS OF THE EARTHQUAKE INVESTIGATION
COMMITTEE. NO. 22. SECTION B. ART. 3.

A Kinetic Measurement of the Modulus of Elasticity

FOR

158 SPECIMENS OF ROCKS:

AND

A NOTE ON THE RELATION BETWEEN THE KINETIC AND STATIC MODULI.

BY

S. KUSAKABE, *Rigakushi.*

With Plates I–II.

Introduction.

The importance of measuring the elastic constants of rocks by a kinetic method may be easily recognized, from the great deviation of the Newtonian velocity, in the case of sound waves, from the actual one. In No. 17 of "the Publications," the author reported some experimental researches relating to static modulus of elasticity of rocks. A little consideration, however, will show that the value of elastic constants determined by a statical method is but a rough approximation to be used in the discussion of wave velocity. Not only are the rapid alteration of state concerned in the propagation of wave attended with thermal effect, but also, in the case of rocks, the phenomenon of yielding may have great influence to make them further deviate from the actual state.

Possibly sound-experiments is the best method of ascertaining the kinetic modulus of elasticity. The result deduced from such infinitely small strains as in sound vibration is no doubt of great value as regards the elastic property of rocks, and may have a close relation to the propagation of seismic waves. As it may seem strange to speak

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of vibration of such loose rocks as sandstone, the measurement of the kinetic modulus of elasticity is not so easy as in the metallic substances.

The method to be described here is an application of Melde's experiment, combined with the principle of resonance. The number of rocks examined amounts to one hundred fifty eight different specimens collected from various localities in the main land of Japan. There are 23 archaean rocks, 65 palaeozoic rocks, 12 mesozoic rocks and 58 cainozoic rocks. The whole experiment is, indeed, but a beginning in this field of inquiry, and may be strewn as a wreck in course of further progress. Still I hope that it will form a stepping-stone to later investigations

Method of measurement.

The essence of Melde's experiment is that, on one hand, a massive fork excited by a bow or maintained in stationary state by electro-magnet, vibrates in a manner, which is approximately independent of the reactions of any light body, which may be connected with it, while on the other hand, the period of the forced vibration of the light body is determined solely by the period of the force which is supposed to act on the system from without.

The principle of resonance is merely that the kinetic energy or the amplitude of any forced vibration is the greatest possible, when the period of the external force is that in which the system would vibrate freely under the influence of its own elasticity. The number of free vibrations of a string of given length may be easily calculated when we know its linear density and the amount of tension.

The present method is simply as follows :

a. A specimen of rock, whose one end is tightly clamped by a massive vice, is maintained in free vibration.

b. A fine wire of known linear density w is connected with the free end of the specimen and stretched with a known tension.

c. The length l of the above wire, in which the wire vibrates with maximum amplitude is measured.

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The number of free vibrations of gravest mode for a pefectly flexible string is given by

$$n_1 = \frac{1}{2l}\sqrt{\frac{W.g}{w}}$$

where W is the suspended weight to which the tension is due. But if we consider the string as not being infinitely thin, so that the radius of gyration k of the area of its section about an axis through its centre of inertia perpendicular to the plane of bending can not be neglected, which is actually the case for a metallic wire, its stiffness must be taken into account. In the case where the extremity of the wire is constrained to be a node by stretching it over a bridge but there acts no couple to fix its direction, the correction for a circular wire with radius r is given by

$$n_2 = \frac{\pi w^{\frac{3}{2}} E'}{16 l^3 \rho'^2 \sqrt{W.g}}$$

where ρ' and E' are the specific density and the modulus of elasticity of the wire respectively.

Thus, the number of vibration n of the specimen, which is identical with that of the connected wire, is given by

$$n = n_1 + n_2 = n_1 + \frac{\pi w E'}{32 \rho'^2} \frac{1}{n_1 l^4}$$

Another term of correction due to the effect of the wire connected at the free end may be easily known, since the effect of the small load ΔM is the same as a lengthening of the specimen, whose weight is M, in the ratio

$$M : M + \Delta M.$$

On the other hand, the relation between Young's modulus E and the number of vibration of the specimen is given by

$$n = \frac{k}{2\pi L^2} m^2 \sqrt{\frac{E}{\rho}}$$

where k is the radius of gyration and ρ is the specific density of the specimen whose length is L; while m is a constant satisfying the equation

$$\cos m \cosh m + 1 = 0.$$

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The smallest root, 1·875, of course, corresponds to the gravest mode of vibration, while the second root, 4·694, and other successive roots correspond to the higher notes. The frequencies of the series of tones being proportional to m^2, the first over-tone is $2\{\log 4.694 - \log 1{\cdot}875\} \div \log 2 \fallingdotseq 2{\cdot}6$ octaves higher than the gravest tone, so that in the actual case the gravest tone is the only one which can be easily measured.

So far as the method is concerned, the above statements are sufficient and nothing more is required. In laboratory work, however, there are several experimental difficulties to be overcome; especially, the maintenance of vibration and the fulfilment of the condition of a clamped end. The last condition is realised by means of a steel vice of massive construction, weighing ca. thirty kilograms. The vibration is maintained by a periodic impulse.

The distinction of forced from free vibrations is very important, and must be clearly stated. If a vibration is the response of the system to a force imposed upon it from without and is maintained by the continued operation of that force, it is obviously a forced vibration. But it must be remembered that any free vibration which we shall have in laboratory experiment takes its origin necessarily from a force acting upon it from without. At first, there is a forced vibration not less important than its rival, but when the force is removed, though there is no discontinuity in velocity or displacement, but the period of the force is at once exchanged for that natural to the system, and the forced vibration is converted into a free vibration.

In the present case, the specimen whose one end is clamped by the massive vice is tapped periodically by a hammer under electromagnetic maintenance. The frequency of the hammer, which is easily adjustable within wide limits by varying its moment of inertia, is about ten per second; while that of the specimen, as the case may be according to the age of the rock, lies between some three hundred and a thousand per second. Thus, between two consecutive tappings, the number of vibrations of the specimen amounts to some

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thirty or hundred, so that the mode of vibration is necessarily of free nature.

Fig. 1. pl. II is the photograph of the whole arrangement, which is laid on a massive stone projecting from the floor of paved stones. A specimen clamped in the vice is tapped by a hammer, which is supported by a stand and maintained in stationary vibration by an electro-magnet. A fine copper wire, whose radius is about one-twentieth mm., is connected by means of bees wax at the upper end of the specimen and stretched over a bridge by a tension due to a suspended weight. The bridge may slide along an iron bench of length ca. 118 cm. in which a scale is graduated in mm. A microscope is also mounted on the bench to measure the amplitude of the vibrating string. The copper wire, whose breaking tension is ca. 140 grams, was first pulled by a tension of 100 grams for about 30 min. and then used as a vibrating string. During experiments, the tension of about ten or fourty grams is sufficient.

Here it is necessary to remark that, although the vibration of the string is due the periodic force imparted from the specimen, the point of application of the force never corresponds to a loop, but, on the contrary, there is a node in that vicinity. Assuming the impressed force given by the vibrating rock, which is connected with the string at a point whose distance from the bridge is $x=b$, to vary as $F\cos pt$, the amplitude of the motion between the bridge and the rock is approximately given by

$$\gamma\left\{\frac{\sin^2\frac{px}{a}+\frac{f^2x^2}{4a^2}\cos^2\frac{px}{a}}{\sin^2\frac{pb}{a}+\frac{f^2b^2}{4a^2}\cos^2\frac{pb}{a}}\right\}^{\frac{1}{2}}$$

where γ is the amplitude of the specimen measured at the point where the string is connected, and f is the coefficient of friction of the string. This expression takes its greatest value obviously when

$$\sin\frac{pb}{a}=0.$$

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that is to say, when the point of application of the impressed force is a node, the amplification of the forced vibration attains its maximum value.

Preliminary Experiments.

To test the arrangement, the following experiment was made with a tuning-fork of known frequency, giving the following result.

Tuning-fork. Sol. 384 vs.

$W=40.595$ grams. $w=4.77\times10^{-4}$ g/c. $g=979.8$ c/s².

	1st Obs.	2nd Obs.	3rd Obs.	4th Obs.	Mean.	l'.	calculated.
1st Node.	24.0	24.1	24.1	24.0	24.0	24.00	24.0
2nd Node.	47.7	48.4	48.0	47.9	47.9	23.95	47.8
3rd Node.	71.6	71.6	71.4	71.4	71.5	23.83	71.6
4th Node.	95.1	95.8	95.2	95.6	95.4	23.85	95.4

It is easy to see that a nodal point lies somewhere at a point near the origin of the scale-measurement. Let this distance be denoted by a, then the above values of l' corresponds to $l+\frac{a}{N}$ where N is the number of loops contained in the observed segment of the string. Thus a and l being two unknown quantities, they may be easily calculated by the method of least squares. The result is:—

$$a=0.24$$
$$l=23.89$$

whence we have $n=191.9$.

The correction for stiffness, which is inversely proportional to the fourth power of l, is insensibly small in this case.

The result of second experiment with the other string and smaller tension is

$$W=20.908$$
$$w=5.27\times10^{-4}$$

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$$l = 16^{c}.32$$

whence $$n = 191.6$$

The difference between the two and the registered value 192 is within the error of observation.

As to the verification for the condition of a clamped end, the case of tuning-fork with two prongs is wholly out of place: so that the following observations with a prism of soft iron may not be superfluous to be cited here. Everything concerning a specimen being given, the frequency varies inversely as the square of the length of the vibrating portion; consequently the fixedness of the clamped section is very important. In the case of tuning-fork, the matter is somewhat different. Any continuation of the specimen beyond the clamped section would be without effect, as it acquires no motion; but as the first clamp is relaxed, the pitch rapidly falls, in consequence of the increase in length. Thus, in tapping the specimen care must be taken to give no impact to the clamped section, i.e. the specimen should be tapped at a place corresponding to the centre of percussion with respect to the clamped section.

The result of the first observation is as follows:—

$$\rho = 7.779$$
$$b = 0^{c}.763$$
$$L = 13^{c}.4$$
$$W = 30^{g}.718$$
$$w = 5.19 \times 10^{-4}\ g/c$$
$$E' = 1.221 \times 10^{12}$$
$$\rho' = 8.667$$
$$l = 10^{c}.87$$

whence

$$n_1 = 350.3$$
$$n_2 = 0.2$$
$$n = 350.5$$
$$E = 2.029 \times 10^{12}\ \text{c.g.s. unit.}$$

The result of the second observation with another string and smaller tension, in which the direction of motion of the point of attach-

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ment was parallel to the length of the string* is as follows:—

$$W = 11^{g}.065$$
$$w = 5.67 \times 10^{-4}\ \text{g/c.}$$
$$l = 12^{c}.47$$

whence

$$n_1 = 175.3$$
$$n_2 = 0.2$$
$$n = 351.0$$
$$E = 2.034 \times 10^{12}\ \text{c.g.s. unit.}$$

The results obtained in the two different modes of experiment agrees with each other within the error of observation.

The experiments with sandstone and tuff, however, gave very ambiguous results to confound the observer. At first sight, it seems as if there were no definite length with which the string vibrated with maximum amplitude. For instance, in the case of sandstone, the length corresponding to maximum amplitude were as follows:—

$9^{c}.28^{(1)}$	$9.93^{(1)}$	$10.64^{(1)}$	$11.42^{(1)}$	$12.34^{(1)}$	$13.40^{(1)}$	$14.63^{(1)}$
$16.23^{(1)}$	$17.39^{(2)}$	$18.41^{(2)}$	$19.69^{(2)}$	$21.04^{(2)}$	$22.61^{(2)}$	$24.49^{(2)}$
$26.06^{(3)}$	$26.70^{(2)}$	$27.58^{(3)}$	29.43*	$31.53^{(3)}$	$32.53^{(2)}$	$33.89^{(3)}$
$34.62^{(4)}$	36.76*	$39.31^{(4)}$	$40.00^{(3)}$	$41.88^{(2)}$	$43.08^{(5)}$	

Small number in brackets is the number of loops contained in the segment. Those marked with* correspond to a peculiar mode of vibration.

The first adequate supposition is that the elasticity of such loose materials as rocks which compose the earthcrust is not unique, so that they may vibrate with several distinct periods differing from each other. Further it becomes a matter of course that the velocity of propagation of seismic waves is not unique even for a given rock. Taking the case of sandstone No. 3_4, the half wave length with which the string may vibrate with maximum amplitude is either of the following numbers.

$13^{c}.48$ 15.33 16.36 17.20 19.25 21.68 24.67 28.72 34.82 42.89.

* Note that, under these circumstances, the period of the string is *double* of that of the specimen, i.e. the frequency n of the specimen is equal to twice the frequency $(n_1 + n_2)$ of the string.

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If we assume that all these lengths equally correspond to proper vibration of the specimen, the period of vibration will not be unique but proportional to the above numbers. The velocity of longitudinal wave should be, then, proportional to the following series of numbers:—

12.9 11.3 10.6 10.1 9.0 8.0 7.0 6.0 5.0 4.0

In Professor F. Ōmori's papers we frequently find what correspond to the above, relating to the periods and velocities of seismic waves in their successive phases.

Repeated experiments, however, showed that such a multiplicity is the effect of tapping by the hammer, so that varying the period of the impressed force we might obtain another series of maximum values. I do not say that the same explanation may be applied to the case of seismic waves. It may be noted, however, that provided two neighbouring localities have their own periods of free vibration, similar phenomenon may possibly occur as one locality is shaken, forced by the motion of the other locality.

Although the vibration is essentially of free nature, it is rendered intermittent by the periodic interposition of an obstacle, so that a very different result is arrived at. In this case, a vibration of frequency n varies in its amplitude with a frequency m, the last of which being the frequency of the hammer. The amplitude increases very suddenly and it is always positive, so that the motion may be assumed, though in very rough approximation, to be represented by the expression, omitting a constant factor,

$$y = \{\cos 2\pi mt\}^a \cos 2\pi nt.$$

By ordinary trigonometrical transformation, the above expression may be put into the form

$$y = A_0 \cos 2\pi nt + \sum_{\nu=1}^{\nu=a} A_\nu \{\cos 2\pi(n+2\nu m) + \cos 2\pi(n-2\nu m)\}.$$

Thus, it is clear that, in such a case, the amplitude takes its maximum value, provided the length of the string corresponds to any one of the numerous component vibrations.

It will be easily seen that the relative magnitudes of the several

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maximum amplitudes are very different from each other in such a way that the greatest maximum corresponds to the vibration with natural period of the specimen and the smaller the amplitude the more affected by the impressed force. When m is not too small to be compared with n, each maximum may be distinctly observed; but these consecutives more and more approach each other as the ratio $\frac{m}{n}$ becomes smaller and smaller. In the case where the ratio is one-fiftieth or smaller than that, the series of maxima become approximately continuous and practically constitute one maximum with small gradient.

Again, varying the period of the impressed force from m to m', all the lengths corresponding to maximum amplitudes, except that which corresponds to the natural period of the specimen, are changed. When these two facts are taken into account, it is not difficult to determine that natural period of vibration for any specimen at hand.

Let l_α and l_β be the length of string, vibrating with one loop, corresponding to the numbers of vibration $(n+2_\alpha m)$ and $(n+2_\beta m)$ respectively, then for certain length l, which is a common multiple of l_α and l_β, the string vibrates in a peculiar manner apparently with one loop, nodes of one mode of vibration being overlapped by loops of other mode and vice versa.

One example will suffice to explain the method of experiments. In the case of sandstone, the result of one experiment with a brass hammer showed that the string might vibrate with maximum amplitude corresponding to any one of the numbers of vibration

$$410{\cdot}0 \pm 25{\cdot}7\nu$$

where ν is an integer, so that

$$n = 410.0$$
$$2m = 25.7.$$

Other experiment with a lead hammer, in which the moment of inertia was increased, gave other result as follows:—

$$n = 409.3$$
$$2m = 15.3$$

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These two values for frequency in free vibration are equal to each other within the error of observation.

In the above observations, the tension of the string remained constant and equal to

$$W = 30.718 \text{ grams.}$$

To test whether the error of observation is affected by the variation of the constant tension or not, other two observations were made on the same specimen, giving the result

for $W = 20.908$, $n = 411.4$

for $W = 11.065$, $n = 409.1$.

Now, taking the mean of the above four values, the data required to calculate the modulus of elasticity of the sandstone are

$$L = 9^c.9$$
$$b = 1^c.16$$
$$\rho = 2.25$$
$$n = 410.0$$

whence $E = 10.36 \times 10^{10}$ c.g.s. unit.

Experimental Result.

The above rather complicated method of observation was applied to determine the modulus of elasticity for one hundred fifty eight different specimens of rocks, containing 23 archaean, 65 palaeozoic, 12 mesozoic and 58 cainozoic rocks. The following table gives the result, arranged in the order of geological age; for the same geological age, those with larger values for the modulus come before those with the smaller. For the complete discussion of the elastic nature of these rocks, so many different elastic constants as the number of symmetry planes, which can be drawn in these rocks, must be determined. As we have, however, no simple means of examining these symmetry planes, a single modulus of elasticity is determined relating to two mutually perpendicular directions, on the supposition that the material is isotropic. The velocity for longitudinal waves, calculated by the formula

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$$V=\sqrt{\frac{E}{\rho}}$$

is also given in the table. The value given in the table may be different from the actual one of longitudinal waves in various rocks, but it will probably give a rough estimate in so far as our modern seismometry is concerned.

KINETIC MODULUS OF ELASTICITY OF ROCKS.

(158 Specimens).

Specimen No.	Rock.	Locality.	Kind.	Density.	Kinetic modulus of elasticity. E_1	E_2	E.	Velocity of longit. wave.
		ARCHÆAN ROCKS.			{c.g.s. $\times 10^{11}$}	{c.g.s. $\times 10^{11}$}	{c.g.s. $\times 10^{11}$}	{Km./Sec.}
50*	Chlorite schist.	Chichibu.	Metamorphic.	2.96	9.79	12.39	11.09	6.12
9*	Chlorite schist.	Chichibu.	Meta.	2.98	10.69	10.88	10.78	6.02
7_2	Peridotite.	Machiya, Kuji, Ibaraki.	Eruptive. (Altered).	2.61	7.72	9.74	8.73	5.78
8_1	Serpentine.	Yokose, Chichibu.	Erup. (Altered).	2.72	9.05	6.98	8.02	5.43
46_1	Quartz schist.	Kashiwagi, Gumma.	Meta.	2.64	5.99	8.91	7.45	5.31
31_1	Quartz schist.	Onishi, Gumma.	Meta.	2.67	7.66	7.19	7.43	5.28
18_1	Chlorite schist.	Nogami, Chichibu.	Meta.	2.88	6.59	7.19	6.89	4.89
16*	Peridotite serpentine.	Mito, Ibaraki.	Erup.	2.83	6.55	7.07	6.81	4.91
22_1	Gabbro.	Nogami, Chichibu.	Erup.	2.71	5.95	7.26	6.61	4.94
26_2	Chlorite schist.	Kunikami, Chichibu.	Meta.	2.87	5.21	6.35	5.78	4.49
91_1	Chlorite schist.	Chichibu.	Meta.	2.88	5.78	5.37	5.58	4.41
45_1	Chlorite schist.	Nogami, Chichibu.	Meta.	2.77	5.46	5.54	5.50	4.46
26_1	Chlorite schist.	Kunikami, Chichibu.	Meta.	2.82	5.55	5.35*	5.45	4.39
28	Graphite schist.	Onishi, Gumma.	Meta.	2.59	5.39	5.07	5.23	4.50
41a*	Peridotite serpentine.	Kuji Ibaraki.	Erup.	2.78	5.13	4.96	5.04	4.27
24_1	Graphite schist.	Kunikami, Chichibu.	Meta.	2.59	4.88	5.15	5.02	4.41
49_1*	Chlorite schist.	Nogami, Chichibu.	Meta.	2.77	4.84	5.00	4.92	4.22
41b*	Peridotite serpentine.	Kuji, Ibaraki.	Erup.	2.79	4.52	4.86	4.69	4.10
60_1	Gneiss.	Shinshiro, Mikawa.	Meta.	2.59	4.02	4.98	4.50	4.17
17*	Peridotite serpentine.	Ibaraki.	Erup.	2.57	4.21	4.67	4.44	4.16
47_1	Quartz schist.	Onishi, Gumma.	Meta.	2.63	4.82	3.34	4.08	3.94
23_1	Graphite schist.	Kunikami, Chichibu.	Meta.	2.56	4.05	4.02	4.04	3.98
30	Chlorite schist. (Decomposed).	Onishi, Gumma.	Meta.	2.64	3.96	4.11	4.03	3.91

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Specimen No.	Rock.	Locality.	Kind.	Density.	Kinetic modulus of elasticity.			Velocity of longit. wave.
					E_1	E_2	E.	
			PALÆOZOIC ROCKS.					
67_1	Schalsteine.	Asama, Ise.	Sedimentary.	2.98	9.35	9.90	9.62	5.68
12_2	Clay slate.	Miyanomai. Aumi.	Sed.	2.71	9.26	8.84	9.05	5.78
69_1	Pyroxenite.	Yamada, Ise.	Meta.	3.05	8.85	8.87	8.86	5.40
78_b*	Schalsteine.	China.	Sed.	2.77	8.01	8.60	8.30	5.48
78_a*	Schalsteine.	China.	Sed.	2.77	8.34	7.87	8.11	5.41
65_1	Schalsteine.	Kamuro, Ki-i.	Sed.	2.84	8.32	7.80	8.06	5.33
71_1	Limestone.	Akasaka, Mino.	Sed.	2.71	7.82	7.54	7.68	5.33
32_1	Pyroxenite.	Mihara, Gumma.	Sed.	2.90	7.81	7.52	7.67	5.15
2_b*	Clay slate.		Sed.	2.69	7.61	7.47	7.54	5.30
34_1	Adinol slate.	Yono-o, Gumma.	Sed.	2.64	7.54	7.45	7.50	5.33
13*	Limestone.	Aome, Kanagawa.	Sed.	2.65	7.43	7.52	7.48	5.31
2_a*	Clay slate.		Sed.	2.67	7.77	7.13	7.45	5.28
29*	Limestone.	Bukōzan, Mikawa.	Sed.	2.68	6.68	7.11	6.89	5.07
79*	Schalsteine.	Rikuchiu.	Sed.	2.65	6.75	6.70	6.72	5.04
74_1	Limestone.	Akasaka, Mino.	Sed.	2.69	6.66	6.65	6.65	4.97
55*	Limestone.	Musashi.	Sed.	2.63	6.55	6.62	6.58	5.01
71_2	Limestone.	Akasaka, Mino.	Sed.	2.69	6.67	6.30	6.48	4.91
11_b*	Marble.	Hitachi.	Sed.	2.63	6.28	6.14*	6.20	4.86
73*	Sandy slate.	Rikuchiu.	Sed.	2.64	6.13	6.05	6.09	4.81
80*	Schalsteine.	Rikuchiu.	Sed.	2.82	5.77	6.23	6.00	4.62
72_1	Limestone.	Akasaka, Mino.	Sed.	2.69	5.87	6.13	6.00	4.72
59_1	Granite.	Okazaki, Mikawa.	Erup.	2.63	5.92	5.94	5.93	4.75
74*	Clayslate.	Nikkō, Tochigi.	Sed.	2.15	5.69	5.72	5.70	5.15
1_a*	Weathered clayslate.		Sed.	2.31	5.13	5.93	5.53	4.89
87_1	Ophicalcite.	Arakawa, Chichibu.	Erup.	2.65	4.91	5.30	5.11	4.39
21_1	Limestone.	Nogami, Chichibu.	Sed.	2.64	5.31	4.76	5.04	4.37
1_b*	Weathered clayslate.		Sed.	2.30	4.97	4.58	4.77	4.55
9_1	Granite.	Mikage, Hyōgo.	Erup.	2.54	4.88	4.61	4.75	4.32
76_1	Slate.	Atago, Kyōto.	Sed.	2.24	4.61	4.83	4.72	4.59
40_1	Micaschist.	Fudō-tōge, Ibaraki.	Meta.	2.54	4.25	4.81	4.53	4.22
69*	Granite.	Schōdō-Jima, Kugawa.	Eruptive.	2.57	4.53	4.42	4.47	4.17
81_1	Granite.	Tamba.	Erup.	2.62	4.46	4.46	4.46	4.13
64_1	Granite.	Nishiura, Mikawa.	Erup.	2.61	4.53	4.30	4.42	4.11
66_2	Granite.	Shirakawa, Kyōto.	Erup.	2.62	4.28	4.01	4.14	3.98
79_1	Slate.	Narutaki, Kyōto.	Sedimentary.	2.45	3.90	4.26	4.08	4.09
75_1	Limestone.	Akasaka, Mino.	Sed.	2.72	3.55	4.59†	4.07	3.87
66_1	Granite.	Shirakawa, Kyōto.	Erup.	2.62	4.03†	—	—	3.93
6_2	Marble.	Maiyama Kuji.	Sed.(Metamorp.)	2.68	3.43	3.89	3.69	3.71
3_b*	Clayslate.	Tamba.	Sed.	2.39	3.63	—	—	3.90
$C0_b$*	Weathered clayslate.	Yamashiro.	Sed.	2.31	3.65	3.49	3.57	3.94

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Specimen No.	Rock.	Locality.	Kind.	Density.	Kinetic modulus of elasticity. E_1.	E_2.	E.	Velocity of longit. wave.
44_1	Granite.	Hyōgo.	Erup.	2.59	3.49	3.33	3.41	3.63
63_2	Granite.	Nishiura, Mikawa.	Erup.	2.84	3.35	3.37	3.36	3.44
12_a*	Marble.	Hitachi.	Sed.	2.65	3.35†	—	—	3.56
10_2	Granite.	Kitagi, Kagawa.	Erup.	2.57	3.24	—	—	3.55
63_1	Granite.	Nishiura, Mikawa.	Erup.	2.84	3.40	3.02†	3.21	3.36
60_a*	Weathered clayslate.	Yamashiro.	Sed.	2.32	3.66	2.72†	3.19	3.72
3_a*	Clayslate.	Tamba.	Sed.	2.38	3.17	—	—	3.65
78_2	Slate.	Narutaki, Kyōto.	Sed.	2.42	3.13	3.16	3.14	3.59
12_b*	Marble.	Hitachi.	Sed.	2.65	3.68†	2.60†	3.14	3.44
78_1	Slate.	Narutaki, Kyōto.	Sed.	2.44	3.08†	—	—	3.55
80_1	Slate.	Atago, Kyōto.	Sed.	2.36	2.99	3.00	3.00	3.56
27_1	Micaschist.	Motoizumi, Chichibu.	Meta.	2.63	2.71	3.15	2.93	3.35
29_1	Limestone.	Onishi, Gumma.	Meta.	2.66	2.40	2.85	2.63	3.15
64_a*	Clayslate.	Inokura, tochigi.	Sed.	2.46	2.63	2.46	2.54	3.21
82_1	Contact slate.	Tamba.	Sed.	2.33	2.75	2.23	2.49	3.27
68*	Granite.	Kitagi, Kagawa.	Erup.	2 55	2.19	1.67†	1.93	2.79
52*	Granite.	Fukuhara, Ibaraki.	Erup.	2.50	1.80†	—	—	2.68
7_a*	Weathered clayslate.	Ōizumi, Hitachi.	Sed.	2.50	1.53	1.58	1.56	2.50
65_a*	Weathered clayslate.	Ōizumi, Hitachi.	Sed.	2.49	1.54	1.53	1 53	2.48
7_b*	Weathered clayslate.	Ōizumi, Hitachi.	Sed.	2 50	1 51	1.44	1.47	2.43
65_b*	Weathered clayslate.	Ōizumi, Hitachi.	Sed.	2.50	1.38	1.37	1.37	2.34
56*	Granite.	Iwase, Ibaraki.	Erup.	2.53	1.36	1.20	1.28	2.25
71*	Granite.	Iwase, Ibaraki.	Erup.	2 59	1.28	1.23	1.25	2.20
42_1	Mica schist.	Tsukioka, Ibaraki.	Meta.	2.64	1.08	1.29	1.19	2.12
61_1	Pegmatite.	Hōjō, Ibaraki.	Erup.	2.57	1.16	1.10	1.13	2.10
		MESOZOIC ROCKS.						
53*	Clayslate.	Ishinomaki, Miyagi.	Sed.	2.70	7.80	7.39	7.59	5.30
77*	Schalsteine.	Akamagaseki, Nagato.	Sed.	2.78	6.46	6.52	6.49	4.85
72*	Clayslate.	Okatsu, Rikuzen.	Sed.	2.71	6.54	6.38	6.46	4.89
76*	Clayslate.		Sed.	2.71	6.42	6.38	6.40	4.86
62_a*	Clayslate.	Tsushima.	Sed.	2.68	4.39	4.25	4.32	4.02
68_1	Granite.	Yoshima.	Erup	2.61	3.42	3.40	3.41	3.62
5*	Sandstone.	Wakayama.	Sed.	2.22	1.32	1.50	1.41	2.52
85_1	Sandstone.	Kiushiu.	Sed.	2.34	1.29	1.30	1.30	2.36
6_b*	Sandstone.	Tanabe, Ki-i.	Sed.	2.22	1.23	1.00	1.11	2.23
83_1	Sandstone.	Kiushiu.	Sed.	2.09	1.03	1.07	1.05	2.24
84_1	Sandstone.	Kiushiu.	Sed.	2.24	1.02	1 05	1.03	2.15
6_a*	Sandstone.	Tanabe, Ki-i.	Sed.	2.24	1.02	0.95†	0.98	2.09

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Specimen No.	Rock.	Locality.	Kind.	Density.	Kinetic modulus of elasticity.			Velocity of long. wave.
					E_1.	E_2.	E.	
			CAINOZOIC ROCK.					
51_1	Andesite	Shinano.	Erup.	2.61	4.37	4.35	4.36	4.09
17_2	Andesite.	Haruna, Gumma.	Erup.	2.63	4.17	3·94	4.06	3.94
1_1	Andesite.	Nebukawa, Sagami.	Erup.	2.59	3.96	—	—	3.91
54*	Andesite.	Nebukawa, Sagami.	Erup.	2.56	4.12	3.53	3.83	3.87
35_1	Sandstone.	Mitagawa, Chichibu.	Sed.	2.47	3.65	3.41	3.53	3.78
1_2	Andesite.	Nebukawa, Sagami.	Erup.	2.59	3.45	3.59	3.52	3.69
15*	Andesite.	Motokomatsu, Sagami.	Erup.	2.20	3.32	3.10	3.21	3.82
52_1	Rhyolite.	Hōraizi, Mikawa.	Erup.	2.20	3.20	3.08	3.14	3 80
57_1	Porphylite.	Ōmi, Mikawa.	Erup.	2.29	3.31	2.92	3.12	3.70
51*	Rhyolite.	Honbun, Izu.	Erup.	2.32	3.12	3.10	3.11	3.66
50_1	Andesite.	Nakatsugaru, Mutsu.	Erup.	2.69	2.79	2.90	2.85	3.26
14*	Tuff.	Nanasawa, Sagami.	Sedi.	2.22	2.91	2.66	2.79	3.55
28*	Andesite.	Izu.	Erup.	2.17	2.49	2.87	2.68	3.52
30*	Tuff.	Kiga, Izu.	Sed.	2.17	2.51	2.64	2.57	3.45
8_a*	Rhyolite tuff.	Iyo.	Sed.	2.35	2.48	2.36	2.42	3.21
39*	Andesite.	Yokone, Izu.	Erup.	2.40	2 39	2.35	2.37	3.14
10*	Tuff.	Yoshida, Izu.	Sed.	2.28	2.29	2.39	2.34	3.21
70*	Andesite.	Shinkomatsu, Sagami.	Erup.	2.46	2.40	2.23	2.31	3.07
58_1	Sandston.	Yebi, Mikawa.	Sed.	2.21	2.33	2.27	2.30	3.23
8_b*	Rhyolite tuff.	Iyo.	Sed.	2.32	2.22	2.38	2.30	3.15
19_c*	Tufaceous sardstone.	Tomioka, Kōtsuke.	Sed.	2.32	2.15	2.31	2.23	3.10
56_1	Tufaceous sandstone.	Yebi, Mikawa.	Sed.	2.12	2.17	2.12	2.15	3.19
63_a*	Rhyolite tuff.	Nakura, Mikawa.	Sed.	2.15	2.15	2.11	2.13	3.14
19_a*	Tufaceus sandstone.	Tomioka, Kōtsuke.	Sed.	2.31	2.08	2.01	2.04	2.97
59_b*	Rhyolite.	Kōtsuke.	Erup.	2.45	1.94	1.93†	1.94	2.82
53_1	Rhyolite tuff. (Weathered)	Hōraiji, Mikawa.	Sed.	2.16	1.78	1.87	1.83	2.91
4_a*	Tuff.	Kawatsu, Izu.	Sed.	1.84	1.78	1.84†	1.81	3.14
59_a*	Rhyolite.	Kōtsuke.	Erup.	2.47	1.88	1.64	1.76	2.67
67_a*	Andesite tuff.	Kami-midera, Yechizen.	Sed.	2.44	1.74	1.73	1.73	2.66
57*	Tuff.	Nawazi, Izu.	Sed.	2.04	1.67	1.70†	1.69	2.88
$6_7$7*	Andesite tuff.	Kami-midera, Yechizen.	Sed.	2.40	1.63	1.72	1.68	2.65
54_1	Tufaceous sandstone.	Hōraiji, Mikawa.	Sed.	2.07	1.55	1.63	1.59	2.77
46_b*	Andesite.	Manazuru, Sagami.	Erup.	2.55	1.56	1.55	1.55	2.47
2_1	Tuff.	Kawatsu, Izu.	Sed.	1.91	—	1.50	—	2.80
40*	Andesite.	Haku-chōba, Sagami.	Erup.	2.30	1.54	1.45	1.49	2.54

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Specimen No.	Rock.	Locality.	Kind.	Density.	Kinetic modulus of elasticity.			Velocity of long. wave.
					E_1.	E_2.	E.	
61_b*	Rhyolite tuff.	Iwashiro.	Sed.	2.20	1.46	1.48	1.47	2.59
35*	Tuff.	Izu.	Sed.	1.85	1.65	1.27	1.46	2.81
49_b*	Andesite.	Mikura, Izu.	Erup.	2.31	1.46	1.39	1.42	2.54
4_b*	Tuff.	Kawatsu, Izu.	Sed.	1.82	1.45	1.39	1.42	2.79
55_1	Tufaceus sandstone.	Hōraiji, Mikawa.	Sed.	2.09	1.44	1.35	1.39	2.58
47*	Andesite.	Yenoura, Shiruga.	Erup.	2.43	1.36	1.35	1.35	2.36
61_a*	Rhyolite tuff.	Iwashiro.	Sed.	2.23	1.37	1.30	1.34	2.45
22*	Tuff.	Izu.	Sed.	2.01	1.30	1.35	1.32	2.56
58*	Sandstone.	Chōshi, Chiba.	Sed.	2.35	1.35	1.26	1.30	2.35
5_2	Rhyolite.	Midera, Yechizen.	Erup.	2.40	1 09	1.28	1.18	2.22
16	Andesite	Haruna, Gumma.	Eruptive.	2.32	1.21	1.14	1.18	2.26
32*	Rhyolite tuff.	Mitaka, Izu.	Sed.	1.89	1.21	1.02	1.11	2.42
37*	Quartz sandstone.	Hizen.	Sed.	2.23	1.02	1.21	1.11	2.23
38*	Andesite.	Katsuragi, Izu.	Erup.	1.94	1.05	1.17	1.11	2.39
4_3	Sandstone.	Tanabe, Kii.	Sed.	2.25	1.04	1.13	1.08	2.19
23*	Andesite tuff.	Yema, Izu.	Sed.	1.83	1.00	0.98	0.99	2.33
34*	Andesite.	Manazuru, Sagami.	Erup.	2.02	0.96	0.95	0.95	2.17
66*	Rhyolite tuff.	Amakusa Hizen.	Sed.	2.26	0.96†	0.62†	0.79	1.87
31*	Tuff.	Teishi, Izu.	Sed.	1.92	0.78	0.77	0.78	2.02
48*	Andesite.	Izu.	Erup.	2.10	0.63	—	—	1.73
3_2	Sandstone.	Chōshi, Chiba.	Sed.	2.20	0.56	0.62	0.59	1.63
21*	Andesite tuff.	Izu.	Sed.	1.50	0.42	0.50	0.46	1.76
35*	Tuff.	Izu.	Sed.	1.29	0.26†	—	—	1.43

N.B. The specimens marked with * are those whose elastic constants were already determined by Professor H. Nagaoka, following a statical method, and published in Pub. of the E. I. C. in F. L. No. 4 1900; Phil. Mag. Vol. 2. July, 1900.

The specimens marked with † are those which were found to have been broken in their clamped portion during the experiment, so that the values given in the table are probably more or less erroneous due to imperfect clamping.

General Conclusion.

Representing the elastic constant of rocks, classified according to the age of formation, by means of "the height from a fixed base line," Fig. 2, Pl. II, we find a distinguished gradation as we pass from the rocks of archaean age to those of cainozoic. Some of recent age may, of course, have greater modulus of elasticity than those belong-

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ing to older period. As a whole, however, archaean rocks come in the first of all, while cainozoic rocks come in the last.

In so far as the present experiments go, the greatest and the least of one group are respectively greatest than those of more recent group in turn. Even for a given rock, the modulus seem to become less for that of recent formation. To take an example, of palaeozoic rocks, the mean value for six specimens of schalsteine and fourteen specimens of granite of various localities are

$$E=7.80\times10^{1}$$

and $E=3.60\times10^{11}$ c.g.s. unit respectively, while for the specimens of schalsteine and granite of mesozoic age, the modulus is

$$E=6.47\times10^{11}$$

and $E=3.41\times10^{11}$ c.g.s. unit respectively.

The modulus of elasticity for a given rock may also vary within wide limits, as density and other physical properties differ for each specimen. For instance, in the case of granite, a specimen from Okazaki in Mikawa District has

$$E=5.93\times10^{11}$$

while that from Iwase in Ibaraki prefecture has only

$$E=1.25\times10^{11}\ \text{c g.s. unit.}$$

It must not, however, be misunderstood that the specimens from two different localities have necessarily different values. In the case of schalsteine, e.g., a specimen from China has

$$E=8.11\times10^{11}$$

while that from Kamuro in Kii District has a nearly equal value

$$E=8.06\times10^{11}\ \text{c.g.s. unit.}$$

For engineers, it should be well remarked that any more compact specimen which has greater density has not necessarily greater modulus of elasticity. For instance, in the case of Andesite, "Honkomatsu-Ishi" from Sagami District has its modulus of elasticity thirteen per cent greater than "Kanehira-Ishi" from Mutsu District, while the latter has its density twenty-two percent greater than the

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former. Again, a piece of granite from Nishiura in Mikawa District has its density twelve per cent greater than that from Mikage, while the latter has its modulus of elasticity, on the contrary, fourty-eight per cent greater than the former. That a material has greater modulus of elasticity and yet less density is what makes it more valuable.

As a general rule, however, rocks of recent formation have less modulus of elasticity and, at the same time, less density than those of old period. The modulus of elasticity of old rocks increase very rapidly, more rapidly, indeed, than proportional to, as the density increases slowly. In Fig. 3, Pl. I. the modulus of elasticity of 158 specimens is plotted against the density of corresponding rocks.

Velocity of propagation for longitudinal waves, as shown in the above table, also increases with age of formation of the rock in reference. It may be noted here that, in so far as the present experiments go, the curve expressing the relation between the density and the velocity is somewhat concave towards the positive part of the axis along which the velocity is measured.

Effect of Moisture.

The present arrangement being unsuitable to give desired moisture to the specimens, it is only intended to test whether the modulus of elasticity is or is not largely affected by the degree of moisture of the specimen.

In the first case, a specimen of sandstone was clamped in the usual way, and the wire stretched with a known tension. When the specimen was in ordinary dry state, it was found that the wire vibrated most violently when the half wave length was 10°.39. Then the specimen was wrapped with a wet cloth in its clamped state and fed with a constant supply of water drops during fourty-two hours to get wet throughout. Now it was found that the corresponding half wave length increased to about a double, i.e. 20°.25, which indicated that the modulus of elasticity decreased to about one-fourth of its original

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value! Not without some doubt on the result, the author waited a whole day till the specimen became apparently dry. Then, the specimen nearly returned to its original state of elasticity, so that the corresponding half wave length decreased to 10^c.65. Heating the specimen by hot air to drive all the moisture, and then cooling it into ordinary temperature, its elasticity increased slightly, the corresponding half wave length becoming equal to 9^c.89. After three hours, the half wave length increased to 10^c.62, showing that the modulus of elasticity was somewhat weakened, returning to its ordinary moisture. The result of such cyclical observations shows clearly that the enormous diminution of the modulus of elasticity by the effect of moisture is an actual fact. The difference between the initial value 10^c.39 and the final value 10^c.65 may be due to some variations of other conditions,—probably a little relaxation of the clamp. As the first clamp is relaxed, it results in the increase of the effective length of the specimen. The last difference corresponds to an increase of about one mm. in the effective length. The following result of experiment may serve to give a rough notion relating to the effect of moisture.

Rock.	Kind and Age.	When it is dry.	When it is wet.
Sandstone.	Sedimentary, Mesozoic.	$\rho_1 = 2.230$, $E_1 = 10.15 \times 10^{10}$	$\rho_2 = 2.351$ $E_2 = 3.173 \times 10^{10}$
Micaschist.	Metamorphic, Palaeozoic.	$\rho_1 = 2.647$, $E_1 = 17.54$	$\rho_2 = 2.669$ $E_2 = 9.21$
Serpentine.	Eruptive, Archaean.	$\rho_1 = 2.708$, $E_1 = 74.55$	$\rho_2 = 2.711$ $E_2 = 62.83$

The above table will teach us at a glance how an important part on the elastic nature of the earthcrust the water plays, which may permeate the earth's surface. To study more closely the effect of humidity, and especially its effect as combined with high temperature, a

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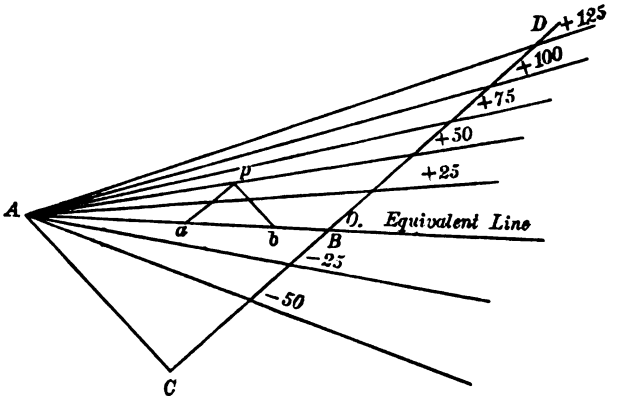
special arrangement is now in preparation, and I hope to be able to write some results on the subject in the near future.*

Relation between the Kinetic and the Static Moduli.

Of 158 specimens given in the above table, a greater part have their elastic constants determined in a statical way, by either Prof. H. Nagaoka or the author himself. Now it is of no small interest to compare the kinetic and the static values for one and the same specimen of rocks.



* The remarkable influence of moisture on the elastic behaviour of rocks, which are not generally deeply embedded in the earth's crust, offers an interesting inquiry into some of the local shocks of earthquakes. With the prevailing rainy weather, there is possibility of the surface rocks being soaked with water. With decreased elastic constants and probably with decreased tenacity, the upper layer of the earth's crust will be subject to increased strain. This evidently will have a tendency to cause rupture, and give rise to feeble local shocks or tremors. The effect will be more felt in regions where the stress distribution is not uniform and the surface stability insecure. It will be of no small interest if such feeble local shocks are to be traced after a long succession of rainy days.

According to the investigations of Mr. Nakamura and Mr. Honda, the level of underground water is affected by the barometric pressure in a most striking manner. Its subsidence and upheaval will to some extent contribute to the variation in the elastic deformation of the surface layers, due to the cause above alluded to. It is however questionable if the variation of the elastic moduli due to moisture arising from this change makes itself felt as tremors or feeble local shocks. H. Nagaoka.

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Here a short remark may be added relating to a new system of co-ordinates specially fitted for percentage representation. Take a right-angled isosceles triangle ABC with its vertex C below the horizontal base AB. Divide the base AB and one side BC into one hundred equal segments, and also in the produced part BD mark off any number of segments equal to one of the last. Join the vertex A with each of the points of section on the side BC and its produced part BD.

Let α and β be the corresponding values of any physical quantity in two different conditions $\mathfrak{A}$ and $\mathfrak{B}$. From A as origin, measure a length equal to α on the side AC or its produced part, then from the end point measure again a length equal to β in the direction parallel to the other side CB. If the last point falls on the base AB, the physical quantity is invariable in the two conditions. If the point, on the other hand, falls on the n^{th} of the previously drawn lines, numbered from the base AB which may be called "equivalent line," then the physical quantity is increased or decreased n percent while the conditions varies from $\mathfrak{A}$ to $\mathfrak{B}$, according as the line is above or below the equivalent line.

In this new system of co-ordinates, the radius vector and the percentage may be considered as two independent variables. This system of co-ordinates somewhat resembles the polar co-ordinates, but one variable "percentage" is not proportional to an angle measured from any fixed line. If a point p (ρ, n) is given, then describe a rightangled isoceles triangle apb, with the given point as vertex and its base ab coinciding with the equivalent line AB. The two segments Aa and Ab represents the corresponding values in two different conditions referred, in a unit multiplied by $\sqrt{2}$.

In Fig. 4, the modulus of elasticity is represented in this co-ordinate system, its static and kinetic values corresponding to α and β of the above illustration respectively. It will be seen, at a glance, that when the radius vector is relatively small, almost every point lies on the positive side, while a greater part of those for which the radius vector is somewhat greater lies on the negative side. General-

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ly speaking, in so far as the present experiment goes, the percentage is enormously great for small radius vector, but it diminishes as the radius vector increases and ultimately it becomes negative. That the percentage diminishes as the radius vector increases is a matter of course, in so far as the phenomenon of yielding is the principal cause which make the two values different from each other. The negative value, however, can never be expected unless some other cause or causes there exist beside the phenomenon of yielding.

Examining more closely, we see that the percentage rapidly diminishes and becomes even negative especially for those rocks which have distinct sedimentation planes as schists and slates. In schistose rocks, the percentage is generally negative, as they have large modulus of elasticity and, at the same time, distinct sedimentation planes. Eruptive rock of any age, be it cainozoic or archæan, has positive percentage. Of sedimentary rocks, those whose modulus of elasticity are comparatively small have also positive percentage, but some of them having large modulus of elasticity may have negative percentage. The following table will show the fact more clearly :—

Rock.	Kind.	Total number of observed specimens.	Mean value of their percentage.	Mean value of their modulus of elasticity.
Sandstone.	Sedimentary.	6	+38	1.57×10^{11} c.g.s.
Tuff.	Sedimentary.	7	+23	1.92
Andesite.	Eruptive.	13	+20	2.12
Granite.	Eruptive.	5	+11	3.14
Slate.	Sedimentary.	17	−6	4.69
Peridotite and serpentine.	Eruptive.	6	+4	6.29
Schists.	Metamorphic.	10	−10	6.39

Here it must be noted that I do not mean to say that the percentange would be always negative for any old rock having distinct sedimentation planes. With all probability, it would be true that the percentage diminishes as the radius vector increases; becoming negative,

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however, may be due to some other causes. The two series of observations have been made with widely different surrounding conditions. The effect of humidity and temperature, for instance, is never negligible, as some of observations were conducted during wet and hot seasons while the other during dry cold season.

Any complete discussion of the relation between the static and the kinetic values must be postponed, at least, until the effect of temperature and humidity on the elastic constants are clearly investigated. The numerical values given above as modulus of elasticity of several rocks, as well as those given in other works, unless the corrections due to temperature and humidity were taken into account serve for nothing more than to give a rough estimation—too rough to compare the results of any two series of observations.

The only conclusion to be properly given is that the result of experiments has only brought him, who thought it at first sight to be a quarry of research that would soon suffer exhaustion, to the threshhold of new labyrinths, where he may find innumerable paths to proceed further. The whole series of observations hitherto made is, indeed, but a beginning in this field of inquiry, and for all the trouble and labour expended to obtain but a poor result, the author is consoled with the saying of Boyle, "men being oftentimes obliged to suffer as much wet and cold and dive as deep to fetch up sponges as to fetch up pearls."

In conclusion, I wish to express my great indebtedness to Dr. Fukuchi, Lecturer in Geological Institute, for valuable informations concerning the geological characters of the specimens. My best thanks are due to Professor H. Nagaoka under whose kind guidance I carried out this experiment.

March 1905.

Physical Laboratory, College of Science,
Imperial University of Tōkyō.

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Art. 3, Kusakabe, Pl. I.

Fig. 2.

Fig. 3.

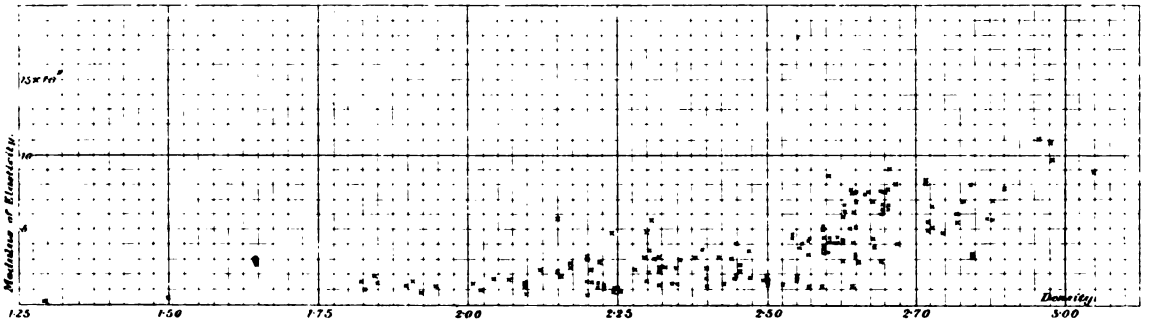
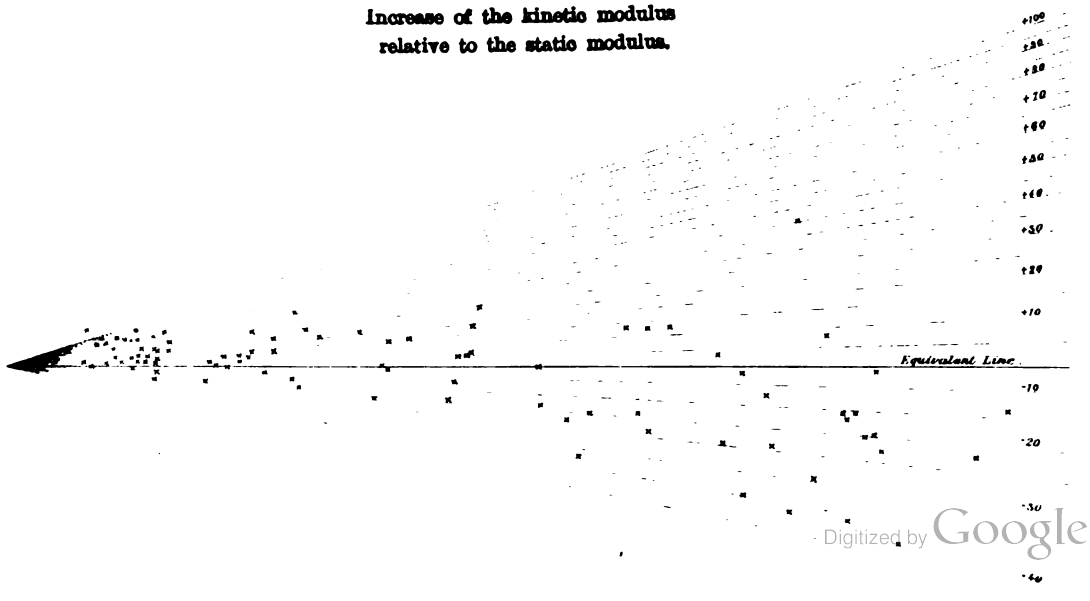


Fig. 4.

Increase of the kinetic modulus relative to the static modulus.



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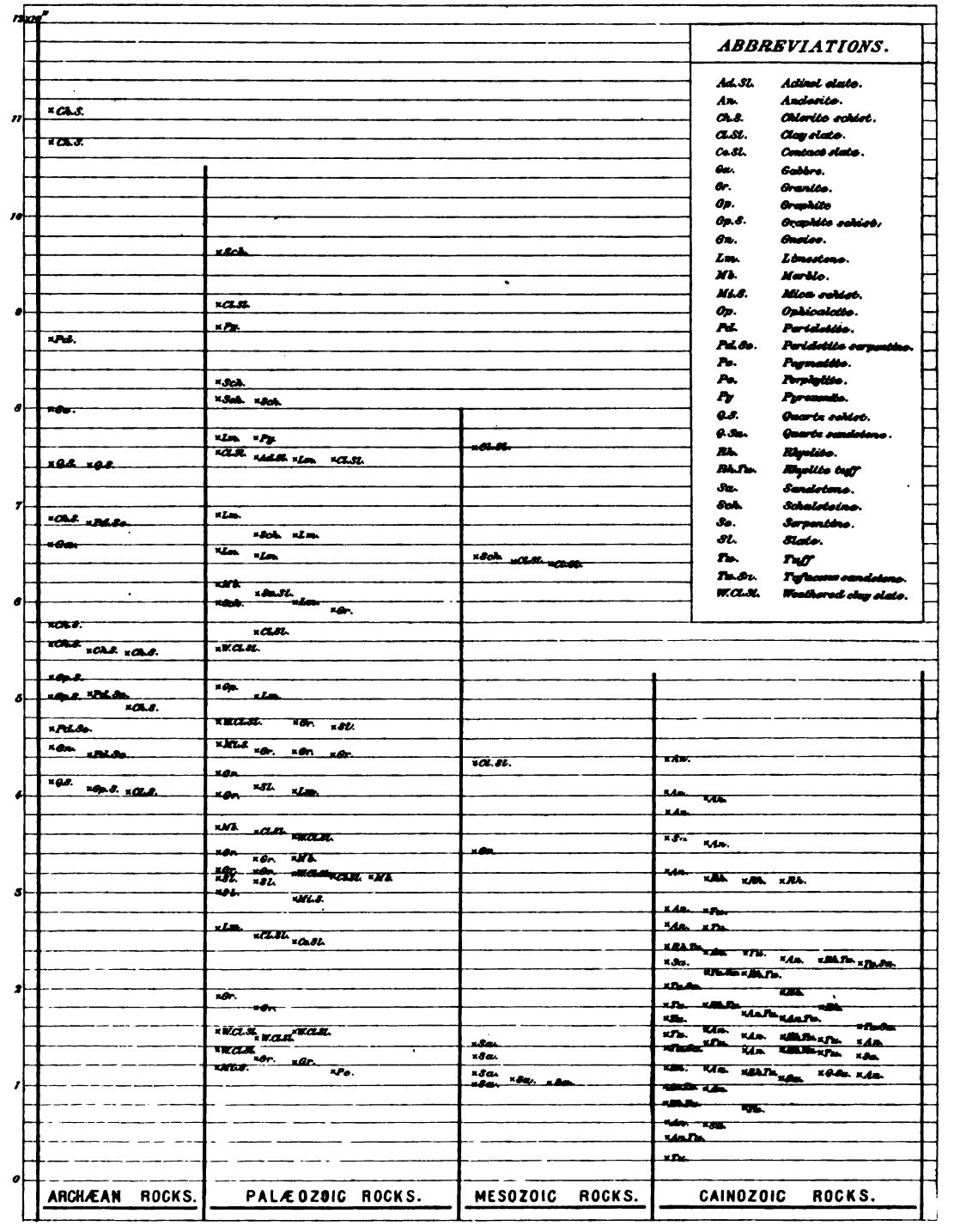
Art. 3, Kusakabe, Pl. II.

Modulus of Elasticity.



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PUBLICATIONS OF THE EARTHQUAKE INVESTIGATION
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On the Geyser in Atami.

BY

K. HONDA and T. TERADA.
Lecturers of Physics, Tōkyō Imperial University.

With Plates I–XII

I. INTRODUCTION.

The remarkable feature of the periodic eruptions of geysers has attracted the attention of many observers. Mackenzie,[1] who travelled in Iceland in 1811 and observed the Great Geyser, first tried to explain the phenomenon; but his theory proved unsatisfactory. Bunsen,[2] travelling on the same island in 1847, made observations on the Great Geyser, and explained the phenomenon by his well-known theory of the vertical pipe. According to him, the origin of the eruption lies in the lower part of the vertical pipe which does not exceed 20m in the case of this geyser. Müller[3] constructed a model after Bunsen and showed that it works periodically, if two portions of the vertical pipe be heated. His theory, however, is not free from objections. Contrary to the Bunsen's view, O. Lang[4] considered the seat of the eruption to lie at a great depth in a canal connected with the vertical one, the water in which acts as a valve for the enclosed vapour. Models given by Julius Ziegler[5] and by G. Wiedemann[6] explain the

1) Mackenzie, Travels in Iceland, 1811.

2) Bunsen, "Physikalische Beobachtungen über die hauptsächlichsten Geysir, Islands," Gehlers Physikalisches Wörterbuch (2te Auflage), LXXII; Pogg. Ann., 72, 1847.

3) Müller, Lehrbuch der Kosmischen Physik, Braunschweig, 1894, S. 619.

4) O. Lang, "Ueber die Bedingungen der Geysir," Göttinger Gelehrten Nachrichten, S. 225.

5) Ziegler, Vorträge des phys. Vereins in Frankfurt a. M., 1872, demonstrated by Dr. Nippoldt.

6) G. Wiedemann, "Ueber einen Apparat zur Darstellung der Erscheinungen der Geysir," Ann. der Phys. u. Chem. (2). 12.

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phenomenon of the geyser from similar points of view. The models consist of a vertical pipe and a large cavity containing hot water and connected to a water tank placed at a suitable height. The constant heating of the cavity produces periodic eruptions of water and steam. Models constructed by J. Petersen, A. Andreae and others[1] do not differ much in principle from those just referred to. The experimental investigations by Andreae[2] and E. Ebert[3] shew that by proper modification of different parts of the models, the several types of eruptions observed in natural geysers can easily be imitated; but the latter remarks that it seems difficult to explain by such a simple theory all the diversities of the manner of eruptions observed in numerous geysers in Iceland, North America and New Zealand.

In Japan, we have two geysers, one at Atami and another at Onikōbe, the force of eruption of the latter being very weak. Twenty years ago, we had another one in Noboribetsu in Hokkaidō, the eruption of which is said to have recurred a few times per hour, projecting hot water a few meters above the ground. At present, it has completely lost its periodical character.

The geyser of Atami is situated on the eastern slope of the coast mountain range of Izu. Its orifice is about 1 km distant from the sea shore and about 22 m above the sea level. Differing from other geysers, the geyser of Atami is characterized by the regularity of its eruption, which consists of alternate projections of hot water and steam, usually five times in succession. The orifice, which originally opened vertically upward, has been covered by a heap of stones to prevent the dangers caused by the eruption, and directed horizontally, so that

1) J. Petersen, "Darstellung der Geysir Erscheinungen," Neues Jahrbuch für Mineralogie, Geologie u. Palaeontologie, 1879, 2.

A. Andreae, "Ueber einen künstliche Nachbildung der Geysir-phänomene," ibid, 1893, 2.

K. Antolik, Zeitschrift f. d. phys. u. chem. Unterricht, 1890–91.

A model given by A. C. Munby, Nature, LXV, p. 247, is of a somewhat different principle.

2) A. Andreae, loc. cit.

3) H. Ebert, "Versuch mit dem G. Wiedemannschen Geysir-Apparat," Ann. d Phys. u. Chem. (2), LXIII.

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the water projected does not return to the mouth, as it does in many other geysers. At present, three orifices (A, a, a', Pl. I) are exposed, among which the one (A) is to be distinguished as the principal opening. There is besides, another mouth, hidden underground. The water projected by these orifices is distributed to numerous bath-houses by a system of conduits.

According to the result of the analysis by Dr. Martin in 1874 and by Dr. Tawara in 1883, the mineral constituents of the water of the spring in 1 litre are as follows;—

Mineral constituents	Martin	Tawara
Solid residuals	10.0104 gr.	9.235 gr.
Sodium chloride	3.79	5.409
Potassium chloride	1.81	0 354
Calcium chloride	1.767	2.893
Magnesium chloride	2.333	0.0145
Calcium sulphate	0.193	0.1313
Ferrous bicarbonate	0.0031	0.002
Calcium bicarbonate	0.0042	trace
Silica	0.110	0.5249
Manganese chloride	trace	trace
Sodium bromide	,,	,,
Potassium bromide	,,	,,

The water is of a strong saline taste, containing about $\frac{1}{2}$ percent of sodium chloride, that is, about one fifth of that contained in sea water.

The ordinary eruption occurs usually five times in a day and night. During the time of repose, we see only a small quantity of steam rising from the mouth. As the time of the eruption approaches, a rumbling sound is heard underneath. Boiling water appears just inside the mouth. It soon retires and again appears. This state is continued for about three quarters of an hour. Next a small quantity

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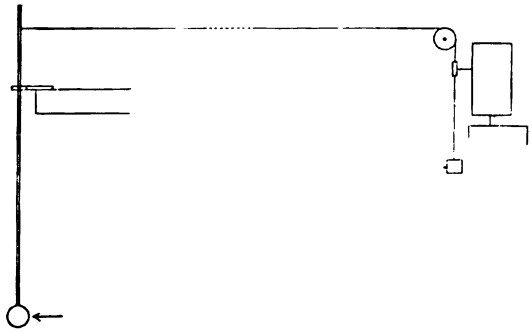
of hot water flows out intermittently. This is followed by an intermittent stream of moderate quantity with a longer period. The activity soon attains its maximum. A torrent of hot water gradually increasing in force, is torn into a violent splash and projected with great velocity by the steam, which gradually increases with the diminishing water. When the roaring sound of the steam reaches its maximum, the water almost disappears. The steam now diminishes and is soon followed by a second gush of water. When these discharges of the water and steam have been repeated five or six times, activity ends with the last discharge of steam, which gradually subsides into an amount as inconsiderable as at the beginning. It takes above two hours from the beginning to the last stage of the eruption. The time of repose is a little less than three hours on the average. These regular recurrences are often interrupted by an abnormal outburst called *nagawaki*, at which the water and the steam come out incessantly for above twelve hours, after which as a rule a long repose follows. In years most noticeable for this anomaly, it has occurred almost monthly, whereas in the last few years only two or three times.

II. ARRANGEMENTS FOR OBSERVATIONS.

To make detailed observations of the general manner of eruptions, the following arrangements were used.



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A pendulum was made of a brass rod, at the lower end of which a lead ball was fixed (3 cm in diameter), and vertically suspended by a short horizontal axis fixed to the rod and pivoted to a catch at the end of a large wooden beam laid horizontally over the principal orifice. The pendulum hung nearly vertically, the lead ball facing closely to the mouth. To the upper end of the rod was attached a string, which passed horizontally to a pulley of the recording instrument. The string after passing over the pulley was attached to a suitable weight. The whole system was so adjusted that the pendulum hung vertically under the balancing action of its own weight and the tension of the string going to the recorder. When the eruption begins, the pendulum is deflected by the pressure of the water and steam. The vertical part of the string below the pulley conveys a pen, which is guided as in the limnimeter[1] used by one of us for recording the level change of artesian wells. The motion of the pen is recorded on a cylinder rotating about a vertical axis. From the records obtained, we can easily distinguish the water and steam-pressure from each other. The part of the record representing the water pressure is much disturbed by zigzags.

Since it was, however, desirable to record the water and the steam separately, the pendulum was transferred to a place in front of the orifice, where all the water ejected flows through a narrow canal to a tank. The whole system was shielded off from the impulsive action of the splash and the steam by a screen of wooden planks. The records thus obtained were completely free from steam pressure.

To record the pressure of the steam only, was a matter of considerable difficulty. Just before the orifice, the steam pressure was tolerably strong; but, there, it was impossible to separate the steam pressure from that of the water. Where the ball of the pendulum did not receive any pressure from the splash of the water, the steam pressure was not strong enough to cause any sensible deflection of the pendulum, so that the arrangement failed to give any

1) K. Honda, Publications of the Imp. Earthq. Inv. Comm., No. 18, p. 73.

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satisfactory result. The aspiration method was also tried, but it failed to produce sensible diminution of the pressure in our recording apparatus. We, at last, adopted the following arrangement, which was essentially nothing more than an air-thermograph. A hollow cylinder or a bulb of iron sheet (radius=2 cm, length=9 cm) was introduced into a side orifice (a), where the water flows out slowly, and where it was possible to find a position such that the bulb was exposed to the heating actions of the steam only. To avoid too rapid expansion and contraction of the enclosed air, the bulb was covered with two layers of cloth. Since this orifice is a small branch of the principal orifice, and the manner of the eruption quite similar for both mouths, the side orifice may be considered as representing the mode of eruption in the principal one on a reduced scale. The bulb was connected by a fine copper capillary tube (diameter=2 mm.) to one of the arms of an U-tube containing mercury. In another arm of the tube, a float carrying a light vertical pen-holder was introduced. The motion of the float caused by the expansion and contraction of the air inside the bulb, was recorded on a vertical drum by the pen, guided as in the case of the limnimeter.

For the statistical investigations, a simple apparatus which might continuously record the exact time of eruption and also, if possible, the general manner of each eruption was desirable. For this purpose, a mercury tide gauge constructed after Mr. S. Nakamura's design[1] erved very well. The lead pipe of the instrument was inserted in the neck of the geyser. At the beginning of activity, the instrument records the periodic level-change of the head of water inside the orifice. When the velocity of the water increases, it records the kinetic pressure of the ejected water. The steam pressure does not display itself on the records. The instrument has been working satisfactorily since the end of March, 1904.

For the determination of the temperature, a maximum thermometer which was graduated up to 150°C, was used.

1) S. Nakamura, Proc. of Tōkyō Math.-Phys. Soc., Vol. I. p. 123.

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III. RESULTS OF OBSERVATIONS.

1. Ordinary Eruption.

a) Flow of water and steam. Fig. 1.

To record the initial stage of eruption, the lead ball of the pendulum was lowered as near as possible to the bed of the canal just outside the mouth, and the small initial quantity of water was compelled to flow entirely through a narrow aperture cut in the edge of a wooden board fixed to the bed close to the mouth. The ball hung just outside the aperture.

Referring to Fig. 1, we see that there exist three distinct series of intermittences. The first series which appears as an introduction to the display, consists of a small quantity of water with an average period of $1^m\,40^s$. After this intermittence has been repeated a score of times, the second series follows. A moderate quantity of water comes out three or four times with a mean interval of 6 minutes. The water increases in quantity and force, till at last the third or principal series sets in. On the first outburst of the third series, we see always the superposition of the last one of the second series. The third series is to be distinguished from the previous series by both its violence and the quantity of the water and steam put out. Besides, the roaring sound of the steam is a remarkable characteristic of this series. The sequence of the water and steam occurs with a mean period of about 11 minutes, and is repeated usually five or six times, not rarely four or seven times.

The pendulum was actuated by the impulsive force of the water and steam; the diagram shows a greatest excursion somewhat later than the actual maximum of the water. In this stage, the velocity of the steam is gradually increasing. When the water decreases to an inconsiderable spray and the steam predominates, the pendulum draws back. The disappearance of zigzags in the curve shows the prevalence of the steam.

b) Flow of water only. Figs. 2 and 3.

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The records are generally similar to those given in Fig. 1, except that in this case, the impulsive pressure of the steam and splash is almost entirely eliminated. In these diagrams, we also see the superposition of the second series at the beginning of the third one. It will be observed that the last one of the third series is often distinguished by the small quantity and the weak force of the water.

c) *Flow of steam only. Figs. 4 and 5.*

In these diagrams, the zero line falls abruptly as soon as the cloth of the bulb is wetted by the condensed steam; this is due to the cooling caused by the evaporation. The ordinate of the curve may be considered as indicating in some measure the velocity of the steam at any instant and hence the area enclosed by this curve and the zero line is a rough measure of the quantity of the steam expelled. In subsequent experiments, it was found better to take the envelope off the bulb, whereby the falling of the zero line is avoided.

When two corresponding diagrams, Figs 2 and 4, or 3 and 5 are placed one upon another so as to bring their abscissae into coincidence, the recurrence of the alternate ejections of the water and steam can clearly be seen.

d) *Level-change during the time of repose. Figs. 6 and 7.*

The end of the lead pipe of the tide-gauge was inserted in the neck of the geyser as deep as possible. It was estimated that the end was only a half meter below the mouth. Since the neck is crooked in a very irregular manner, further attempt to insert the tube deeper than this failed. The record was continuously taken from the end of one eruption to the beginning of the next one.

The diagram obtained reveals to us a remarkable fact that within about 40 to 50 minutes after the end of an eruption, the head of hot water appears within a half meter below the mouth. The head seems to oscillate about its position of equilibrium for about one and a half to two hours, till the next activity begins. This interval may be considered as the time of preparation for the next eruption.

e) *Time of occurrence. Figs. 8, 9 and 10.*

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The end of the lead pipe was drawn up to just inside the mouth. The clockwork gives one revolution every 24 hours. The records have been taken continuously from April, 1904. up to the present. From the statistical investigation of these records, we may infer the following facts:—

i) From April, 1904, to March, 1905, the mean period of the eruption was very nearly 24/5 hours. In May, 1905, there occurred an abnormal decrease of the activity of the geyser and since August of the same year, the activity has decreased to about four times per day.

ii) If the times of occurrences be plotted on a diagram, the successive days as abscissae and the hours of the day as ordinates, we obtain a set of five points per day. Connecting corresponding points, five broken lines are formed. These lines show a striking parallelism with the inverted curve representing the variation of the mean atmospheric pressure for successive days. The high pressure corresponds almost without exception to the short period and the low pressure to the long period.

iii) The sum of the daily intermittence of water and steam given out, taken for the five daily eruptions, is generally abundant on the days in which low pressure prevails. The eruptions in which the alternations of water and steam occur more than eight times, fall in usually with approaching low pressure.

f) Temperature of the hot water during eruptions.

A maximum thermometer was placed about 1.5 m inside the orifice and the temperature has been read daily during about a half year. It was found that the temperature at this depth is almost invariably 103°-104°C. At the orifice, however, it was about 100°C, indicating a rapid cooling of the hot water. It may, therefore, easily be conjectured how hot the underground water would be at a depth of some ten meters.

g) Velocities of the water and the steam.

To determine the velocities of the water and the steam, the pendulum arrangement was modified in the following way. The pendulum bob was replaced by a larger brass one B, and the center of mass of the

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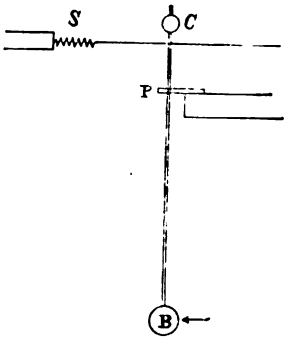
pendulum was brought to the axis of rotation P by using a counterweight C, as shown in the annexed figure. From the upper part of the pendulum rod, two strings were stretched in opposite directions, one of which passed to the recording apparatus, while another one was stretched by a spring s fixed to a rigid support. The weight of the recording apparatus was so adjusted that the rod hung vertically, when it was acted upon by no pressure. When the pendulum was set to work in a proper stage of an eruption, the pressure due to the water and the steam could separately be observed. After the record has been taken in the usual manner, a series of known weights—30, 50, 80, 100, 200, and 300 grams—were successively applied to the pan hanging under the recording pen, and the corresponding deflections of the rod were recorded on the cylinder. From these observations, we could calculate the amount of the pressure exerted by the water and the steam upon the brass ball.



The total pressure exerted by a fluid stream upon a sphere is known to be approximately equal to one half of that upon a circular disc of the same diameter. Hence

$$p=\frac{\pi r^2\rho v^2}{2}, \qquad \text{or} \qquad v^2=\frac{2p}{\pi r^2\rho},$$

where p is the pressure, r the radius of the ball, ρ the density and v the velocity of the water or the steam.

For the water, the maximum velocity was calculated to vary from 1.5 to 2.0 m per sec.

For the steam, the velocity was found to vary from 18 to 24 m per sec., as given in the following table:

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No. of Intermittence	Velocity
1	24 m/sec
2	25—24
3	22—18
4	24—23
5	22—18
6	22—18

In the above calculation, we took for the value of ρ, the density of saturated vapour under atmospheric pressure.

h) *Quantities of water and steam.*

Since the quantity of the water and the steam in each eruption differs considerably for different eruptions, it was sufficient to get a rough estimation of the amount. Again, to make an exact measurement of the total quantity of the water or the steam is almost hopeless, in the present condition of the orifice, as it is branched into several mouths; some of these are hidden underground, whence the hot water is distributed by a number of separate conduits.

The direct method for the quantity of the water was to measure the quantity supplied to a number of tanks and to estimate the total from the section of the conduits. The tanks chosen for this purpose were those of Kyūkikwan and of Sagamiya. The results are:

Kyūkikwan	11^h	p.m,	April 1, '04.	3.38 m^3
Sagamiya	11^h	a.m,	,, 2, ,,	1.28.

Since the numbers of the conduits for the exposed orifices A, a, a′ are 21, 2, 3 respectively, the total quantity of the water will approximately be $1.28 \times 26\ m^3 = 33.2\ m^3$ or 184 *koku*. It was also estimated that the total quantity of the water which flows out from the hidden orifice, is $3 \times 3.38 = 10.1\ m^3$ or 56.3 *koku*. Hence the whole discharge of one eruption will approximately be $45 m^3$ or 250 *koku*. This number is a little greater than that obtained by Dr. Tawara, and nearly coincides with that given by J. Tsuyuki, a resident in Atami.

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The rough estimation of the steam was carried out in the following way. Let the quantity of the steam be denoted by Q, we have

$$Q=\int Sv\rho dt,$$

where Sv is the flux of the steam. If V be the ordinate of the steam diagram, we may put

$$v=kV,$$

$$\therefore \quad Q=S\rho k\int Vdt.$$

In our case, k was found to be 500 and S was estimated to be 300 cm^2. Hence

$$Q=121\int Vdt.$$

For an eruption, we found $\int Vdt=6500$, and therefore

$$Q=800 \text{ kg.} =213 \textit{ kwan}$$

These numbers for the water and the steam must be considered as giving the orders of magnitudes of these quantities.

2. *Abnormal Eruption, the Nagawaki.*

Figs. 11 and 12.

The record of *nagawaki*, kept at Kyūkikwan is given below:

1894: Jan. 6; Feb. 22, 7^h p.m.—23, 11^h a.m.; March 30, 4^h p.m. —31, 6^{h}30^m a.m.; April 30, 6^h a.m.—2^h p.m.; June 7, 5^h a.m. —5^h p.m.; Aug. 20, 4^h p.m.—21, 6^h a.m.; Sept. 27; Nov. 17, 4^h a.m.—4^h p.m.; Dec. 28, 8^h a.m.—8^h p.m.

1895: Feb. 18, 4^h p.m.—19, 5^h a.m.; April 9, 8^h a.m.—5^h p.m.: June 12, 4^h p.m.—13, 6^h 30 a.m.; Aug. 14.

After this date, the record is missing till 1903.

1903: Sept. 8^h p.m.; Dec. 29, 3^h p.m.

1904: None.

The first *nagawaki* recorded by our arrangement began at 4^{h}30^m a.m. on Jan. 14, 1905, from the third series of the ordinary eruption. During two or three days before the *nagawaki*, the period of the

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successive eruptions seems to have been slightly diminished, but in such a degree that may be found not seldom in our records, without leading to either *nagawaki* or anything extraordinary. The *nagawaki* began, as it were, almost suddenly in the midst of an ordinary eruption. As given in Fig. 11, the flow of the water continued without interruption, gradually decreasing in quantity and mixed up with the steam. At 7^h40^m p.m., it came to a sudden repose; at 2^h40^m a.m. on 15th, an intermittent flow of hot water resembling the second series of an ordinary eruption began and continued for about three hours. After a repose of four hours, ordinary eruption at last set in, but with the period remarkably shortened and the general activity strikingly reduced. The number of eruptions per day was ten, a remarkable contrast to the ordinary frequency of five per day. The frequency decreased afterward very slowly with the time (Fig. 12), and recovered its original value after the lapse of about a month.

The second *nagawaki*, which occurred on May 27, 4^h 30^m a.m.—28, 6^h 20^m a.m., '05, was quite similar to the previous one in its general aspects, though it took place in conjunction with an extraordinary decrease of the general activity. The third *nagawaki* occurred on Dec. 13, 6^h p.m.—14, 9^h 40^m a.m., '05, and the fourth on March 6, 6^h 40^m a.m.—7, 2^h a.m., '06. They are quite similar in the general aspects to the one above referred to. It is an interesting coincidence that these *nagawakis* began at the same phase of the ordinary eruption, and that a center of low atmospheric pressure was approaching from the Pacific in each case.

3. *Extraordinary Decrease of Activity.*

Figs. 13 and 14.

During the course of the last few years, several wells have been bored in this district. Many of them give a moderate quantity of hot water only by pumping. In 1905, the number of the wells has been greatly increased, amounting to about twenty in all. Sawaguchi's well bored on March 27, '05, burst out with great force, continuously

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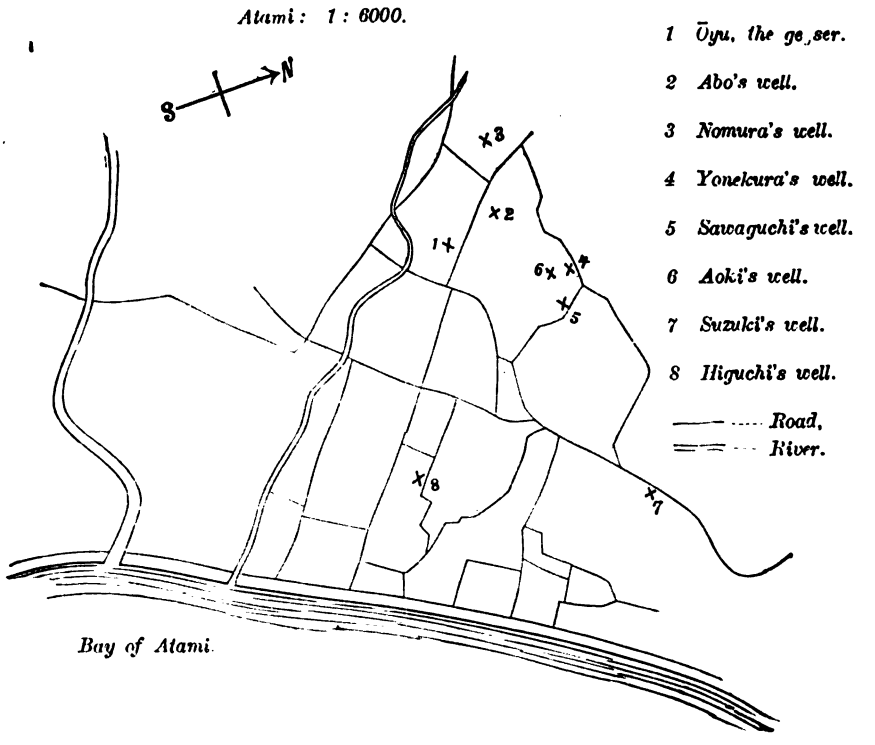

throwing up a column of steam and hot water about 8 m high. On May 22, another, Yonekura's, of a much greater activity was opened within a few hundred meters from the geyser, giving out hot water at a rate of about 310 cubic meters per day. Two days afterwards, still another, Higuchi's, of not much less activity was bored. After the boring of the Sawaguchi's, a slight decrease in the frequency of the geyser was observed; on May 20, it was reduced to 4.4 times per day, though the force of each eruption presented no appreciable change. After the boring of the other two, the frequency of the geyser remarkably decreased; it was 3.6 on May 26. Moreover, the first and the second series of each eruption became considerably longer than usual and the principal series was lessened in force. After the *nagawaki* which occurred on May 27, the number of eruptions per day was temporarily increased to 6, though the quantity of the hot water

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was rather decreased. On June 5, the frequency again fell to 3.6 and on June 11 to only 3.2; the first and the second series were prolonged to three and a half hours, while the principal series was reduced to only three weak eruptions. The consequent decrease in the quantity of hot water caused trouble to several bath-houses supplied by the geyser, and the above three wells which must have been the probable cause of the decrease, were all stopped—Yonekura's on June 12, Sawaguchi's on the next day and Higuchi's on July 12. Immediately after the stoppage of the first two wells, the frequency of the geyser increased to 4 and moreover the preliminary series of each eruption was shortened and the principal eruption gradually tended to regain its original force. After stopping Higuchi's, the frequency gradually increased and attained 4.5 in August, which was still a little short of the original value. Since then, the frequency has gradually decreased to 4 and remained nearly constant up to the present, though it was temporarily disturbed by two *nagawakis*. As to the mode of each eruption, it has quite recovered its original force. It is to be remarked that still new wells remain open, Aoki's, which are near the geyser and give a moderate quantity of hot water.

The stoppage of wells was a matter of no small difficulty. The sight witnessed by us during the stopping of Yonekura's well may be worth recording. The well was about 25m deep and threw up a column of hot water mixed with steam about 8 m high, from an iron pipe of 4 inches diameter. Cylinders of sheet iron filled with sand and pebbles which were intended to stop the well, were violently thrown up in the air when put in the orifice. An iron rod of about 10 kg weight thrown into the mouth was held by the water near the mouth, neither falling nor rising. Next, an iron pipe of 2 inches diameter and of about 6 m length, was filled with sand and forced into the orifice. Though the quantity of the water and steam was considerably lessened by this pipe, the upward pressure still overcame the weight of the pipe and when the pipe was released, it was thrown up into the air about one meter high. Next a similar pipe filled with

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iron bolts and sand was applied. This pipe fell freely down the well. Immediately, the quantity of water was greatly reduced and a number of pieces of tuff imbedded with small crystals of iron-pyrites, was pelted out with the jet of steam and scattered within several meters from the spot. Then another iron pipe was thrown into the hole and cold water was poured down, which completely stopped the activity.

From the fact that the iron bar above described was held in equilibrium by the pressure of the water jet, we may roughly estimate the velocity and the mean density of the splash at the orifice. If w be the weight and S the sectional area of the rod, and if ρ be the mean density and v the velocity of the jet, we have

$$w = S\rho v^2$$

Again, if R be the radius of the orifice and Q the quantity of water given out per second,

$$\pi R^2 v\rho = Q$$

By our previous measurement, $Q = 0.0036$ cubic meter per sec. The result of our evaluation is thus

$$v = 12 \text{ m/sec}; \quad \rho = 0.73,$$

i.e., the jet of water fills up about 7/10 of the area of the orifice. The power of the jet calculated from these data is about 3.5 H.P.

4. *Level Change and Temperature of Artesian Wells.* Figs. 15 and 16.

Level-changes of two wells near the geyser were recorded by means of Honda's limnimeter. Nomura's well, which is within 200 m of the geyser and 25 m above the sea level, shows a regular up and down motion of about 10 cm, five times per day (Fig. 15) corresponding to the eruption and repose of the neighbouring geyser. When the geyser is at the height of its activity, the level of the well is at its maximum. The slow rising of the mean level is partly due to rain. Effects of the tidal and the atmospheric pressure are also recognizable, but not very remarkable. The temperature of the water in this well is 50°-60°C.

In Suzuki's well, situated more remote from the geyser than the

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Nomura's and nearer to the sea, the effect of the geyser is not observed, but the level rises and falls with the tide (Fig. 16). The record shows peculiar zigzags indicating that the surface of the water is continuously disturbed by the boiling. If the water be pumped out a little at first, it continues to flow eruptively for a while, till a definite quantity is reached and then follows repose. If the pump be actuated again after a few hours, a nearly equal quantity of boiling water flows out in a similar way. But, if pumped earlier, a small quantity may be drawn out only after hard pumping. The level of this well is about 11 m below the ground and 22 m above the sea level. On one occasion, the temperature of the water in the well at different depths was measured with a maximum thermometer and found to be remarkably high. The results are given in the following table:—

17.6 m	6.6 m	103°C.	115°C.
26.6	15.6	123°	128°
32.1	21.1	139°	135°
35.7	24.7	140°	138°
44.9	33.9	140°	147°
54.0	43.0	142°	152°

The first and the second column denote the depths measured from the surfaces of the earth and the water respectively; the third column is the actual temperature corresponding to each depth; and the last is the corresponding boiling point of water under pressure, calculated from the Regnault's results. From the above table, we see that the temperature of the water rapidly increases almost proportionally with the depth up to about 20 m from the surface of the water; then the rate of the increase becomes abruptly small. This shows that at about 20 m below the surface of the water, there is a layer or a space between layers in which highly heated water is continuously flowing. At these depths, the actual temperature is a few degrees higher than the corresponding boiling points under pressure, so that the boiling is continuously going on, as shown by the limnimeter set up in the well.

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Here it is to be noticed that the rise of the boiling point due to the dissolved substances is at most one degree.

Abo's well which is situated midway between the geyser and Yonekura's well, is about 33 m deep and gives out hot water by pumping. The results of the temperature measurement at different depths, made by a maximum thermometer, are as follows:

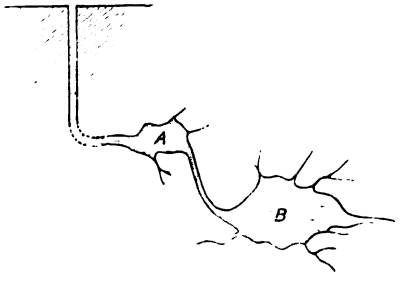
At the water surface	62.0 C.
23.0 m below,	95.5
28.5 „	98.3
29.7 „	104.3
31.0 „	118.2

From the results in these two wells, it is evident that in the district of Atami, there exist layers with very high temperature near the surface.

IV. EXPLANATION OF THE PHENOMENA.

Existing theories are not sufficient to explain the exact manner of the eruption of the geyser of Atami. Wiedemann's model though plausible in many respects, fails when applied to this geyser, in which water and steam are alternately projected several times in succession. We sought, therefore, for other alternatives and constructed several models for experiments.

First, we conceived two subterranean cavities (A and B) connected in series, as shown in the annexed figure and supposed B to begin the eruption earlier than A, by the underground heat. The model constructed according to this supposition worked almost satisfactorily, except that the mode of intermittence in the principal series of the eruption was not quite similar to the actual geyser; for, in this model, the steam predomi-



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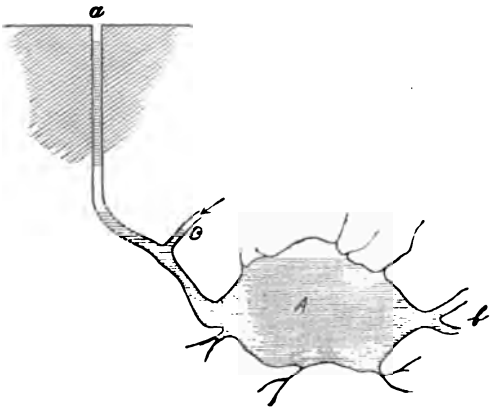
nated toward the end of each eruption, instead of showing a regular alternative intermittence of steam and water as in the actual case.

After a sequence of modifications and experiments under various conditions, we arrived at last at the following theory which seems for the present to be sufficient to explain the phenomena of the geyser in question:—

Referring to the figure, A is a cavity lying at a considerable depth; a is the vertical pipe and b a canal which supplies the water to A. We conceive a side-canal c intermediate between A and a, which leads to a second cavity C, not shown in the figure. The temperature of the water in a and c is supposed to be lower than the corresponding boiling point. Water in A is heated by the wall of the cavity, the temperature of which is supposed to be decidedly higher than the boiling point at that depth. The source of the heat is probably to be attributed to the hot water and steam running through numerous veins and canals extending beneath the district. When the tension of the vapour in the cavity attains its critical value, the water is ejected and then the steam follows. When a certain amount of the steam is given off, the pressure in the neck is reduced to such a degree that the water flows in from the side-canal and stops the eruption momentarily. Soon, the downward pressure of the water column is overcome by the tension of the vapour and the second gush follows. These eruptions are repeated several times, till the vapour pressure is so reduced as to admit the comparatively cold water from the feed-canal b and also from c. Thus the activity is quenched for a while till the next eruption begins.



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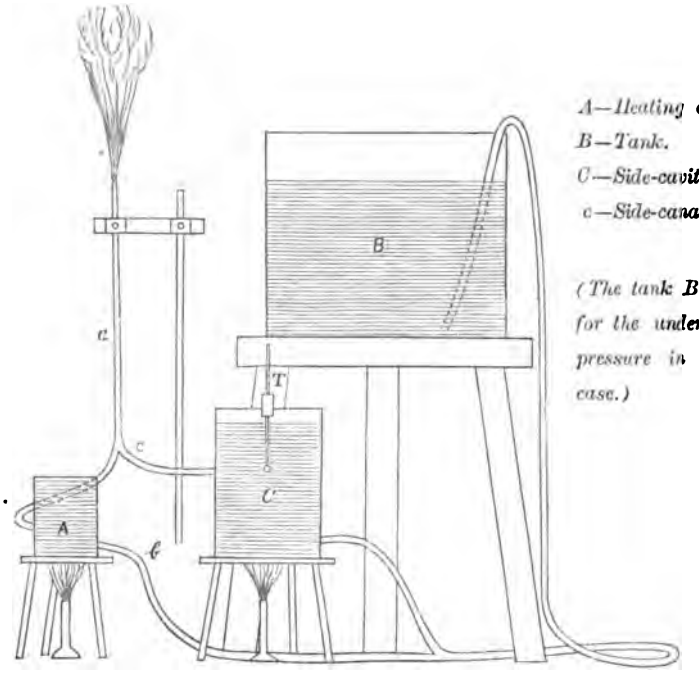

A—Heating cavity.
B—Tank.
C—Side-cavity.
c—Side-canal.

(The tank B stands for the underground pressure in actual case.)

A model constructed according to this view worked satisfactorily. Referring to the figure, A is the working cavity, c the side-canal fed by the second cavity C larger than A. B is the large tank supplying A and C; a is a glass tube representing the vertical pipe of the geyser. These are all connected by cauchouc tubings as shown in the figure. Both A and C are made of brass, thickly covered with asbestos to prevent cooling, and moreover, are provided with glass gauges showing the water levels inside. The cavities filled with water are heated by proper Bunsen burners, care being taken to keep the temperature of the water in C somewhat below the boiling point—the temperature being read by the inserted thermometer T. We give below the dimensions of the principal parts of our model:—

Capacity of A: Height = 13.0 cm; Diameter = 9 cm.
„ „ C: „ = 18.5 cm; „ = 15 cm.
Height of the orifice above the bottom of A = 1 m.

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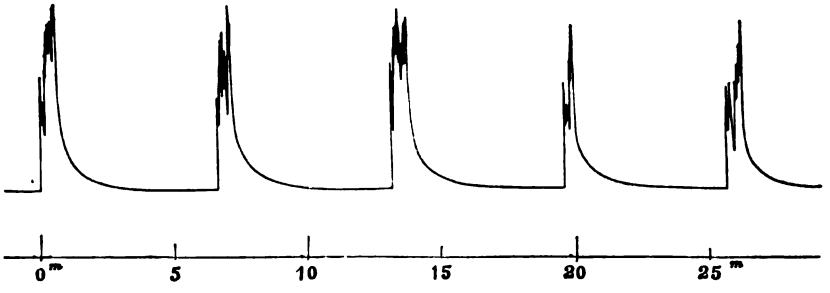
Internal diameter of the vertical pipe = 5 mm.
Diameter of the orifice = 2.5 mm.
„ „ „ tube b = 7 mm.
„ „ „ „ c = 5 mm.

The period of the eruption depends on the heating of the cavity A, increased heating shortening it. The number of the intermittences increases with the temperature of the water in C. In our experiments, the mean period of the eruption was 6.5 minutes and when the temperature in C was 95°C, the number of intermittences in each eruption was 3 to 4.

In this way, the manner of the eruption was imitated even in its details. The figure here given is one of the records of the eruption



of our model, obtained by the air-thermograph already mentioned. The preliminary series of the eruption was not recorded by this arrangement, in which the air-bulb was placed somewhat high above the orifice.

The phenomena of *nagawaki* may be explained partly by the supposition that the underground temperature is raised above its normal value and so the temperature of the cavity C becomes higher than the ordinary value. If the temperature of the cavity C in our model be raised to a certain value, the eruption corresponding to *nagawaki* begins. It resembles the actual one even in some details. The cause of this occasional change of the temperature is probably the change of the subterranean volcanic activity, which keeps the underground temperature in this district considerably above the boiling point of water.

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The fact that the frequency of the eruptions immediately after *nagawaki*, is nearly doubled, may partly be explained, if we consider that the temperature of the heating cavity is raised during the course of the *nagawaki* by the incessant flowing of superheated water. It may be added as a very suggestive fact that if in our model, a quantity of air be blown into the heating cavity, the frequency of the eruption increases remarkably at first and then gradually decreases with the gradual expulsion of the air by the successive eruptions; even the weakness of the activity in the actual case is imitated with great faithfulness. During a few hours after *nagawaki*, the cavity as well as the canals leading to the orifice remain drained out, so that it is possible that air or other gases may enter into the cavity and cause the increased frequency of the eruption.

It is a fact of common observation that the temperature of some ordinary hot springs rises with the low atmospheric pressure. This is undoubtedly due to the increase of the flow caused by the enhanced circulation due to the reduction of the pressure. If in the supposed heating cavity of the geyser, the interchange of the water due to the slow circulation through numerous veins and fissures be accelerated by some cause, the time required for the sufficient heating for the eruption must necessarily be prolonged. This consideration seems to explain the influence of the atmospheric pressure on the period of the eruption above mentioned. Again, the probable influence of the well-boring on the geyser, may be explained on the same basis. The wells may increase the circulation of the underground water in the vicinity and result in the retardation of the eruption of the geyser in a similar manner. Moreover, it is quite natural that the hot water would find its easier vent through a new passage opened with less resistance, at the expense of the quantity originally ejected by the old one alone. The prolongation of the first and second series of the eruption, suggests the slowness with which the pressure in the heating cavity approaches the critical value. Careful investigation of the change in the wells, leads us to the strong belief that the striking

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coincidence of the well-boring and the extraordinary decrease of the change in the geyser, is a necessary and not an accidental one. If the frequency of the eruption does not yet quite attain its former value, long after the stopping of the wells, we need not wonder at all, since some irreversible change in the subterranean mechanism might have happened during the period of the disturbance.

It should be noticed that almost simultaneously with the beginning of the abnormal decrease of the activity, severe shocks of earthquake were felt in the Island of Ōsima, an active volcano situated in front of Sagami Bay, about 27.5 miles from Atami. On this account, it was generally believed that the decrease was the consequence of some change of the subterranean activity associated with the earthquake. The belief seems to have its origin in the tradition that the occurrence of *nagawaki* has some relation to the activity of Ōsima. But, judging from the manner of the change of the geyser accompanying the boring and stopping of the wells, we are inclined to believe that the principal cause of the disturbance is to be attributed to the well-boring.

The question naturally arises as to the actual source of the immense quantity of the hot water poured out daily by this geyser. It seems, according to the accepted view of the modern geologists, that the water condensed from the superheated steam coming from the very depth of the earth's crust forms a considerable part of the mineral water of such a hot spring. Accepting this as a partial explanation, we feel inclined to trace the greater part of the hot water ejected by this geyser to the underground water circulating at a comparatively small depth heated by the extraordinary heat under the district. The presence of the sea-water constituents in the water of the geyser is probably due to the sea-water penetrating through several fissures in the neighbouring bay, which bears strong geological evidence to having once been the crater of an volcano.

In conclusion, we wish to express our best thanks to Mr. S. Kusumi, the apotheker to Kyūkikwan, to whom we are very much indebted for his zealous assistance during the course of our observations.

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General View of Atami.

Rising steam of the geyser to the left of the scenery.

Geyser in Repose.

A; principal orifice; *a*, *a'*: minor orifices. Lead tube to the mouth.

Geyser in Full Activity.

White sprays colliding with rocks to the left.

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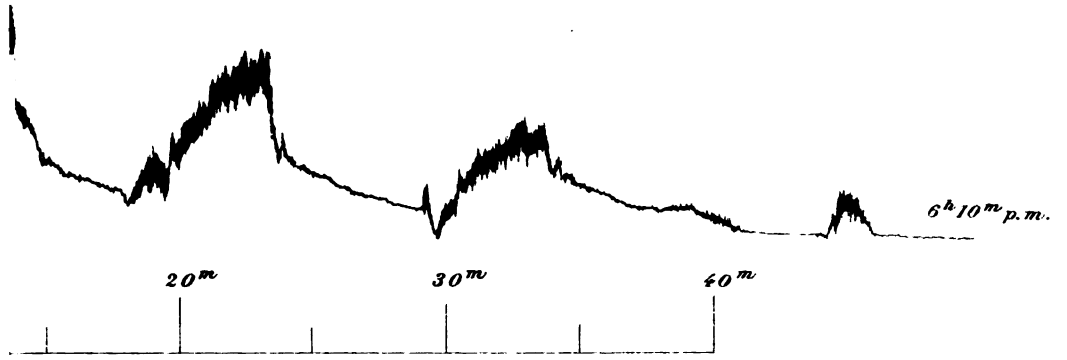

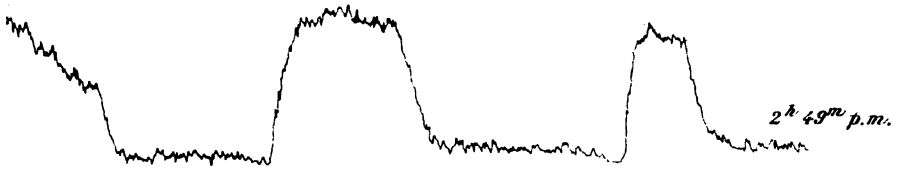

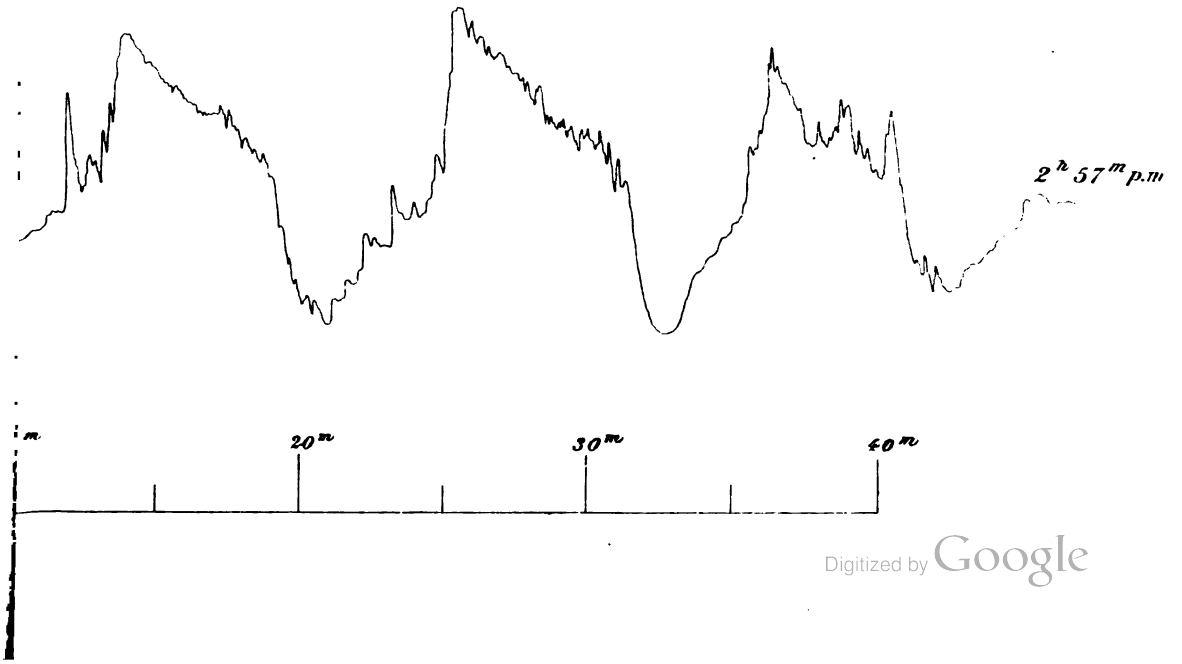

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Fig. 1. March 26th, 1904.

Fig. 1.

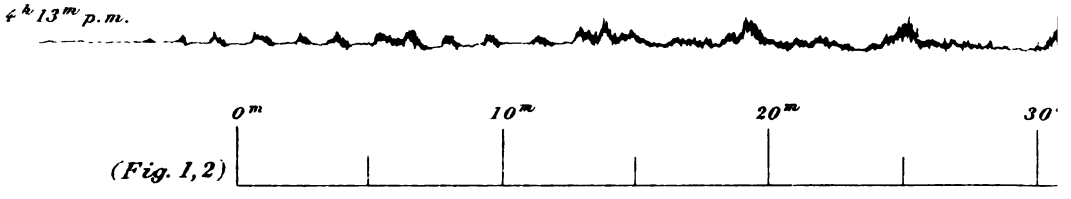
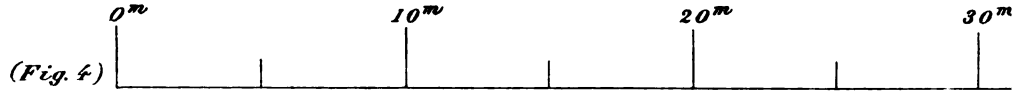


Fig. 2. March 31th, 1904.

Fig. 2.

Fig. 4. March 31th, 1904.



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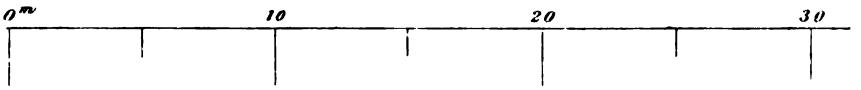

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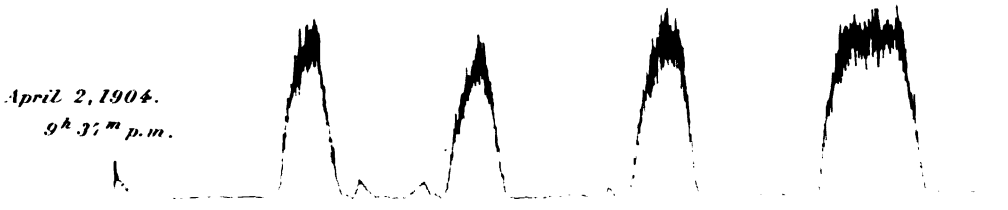
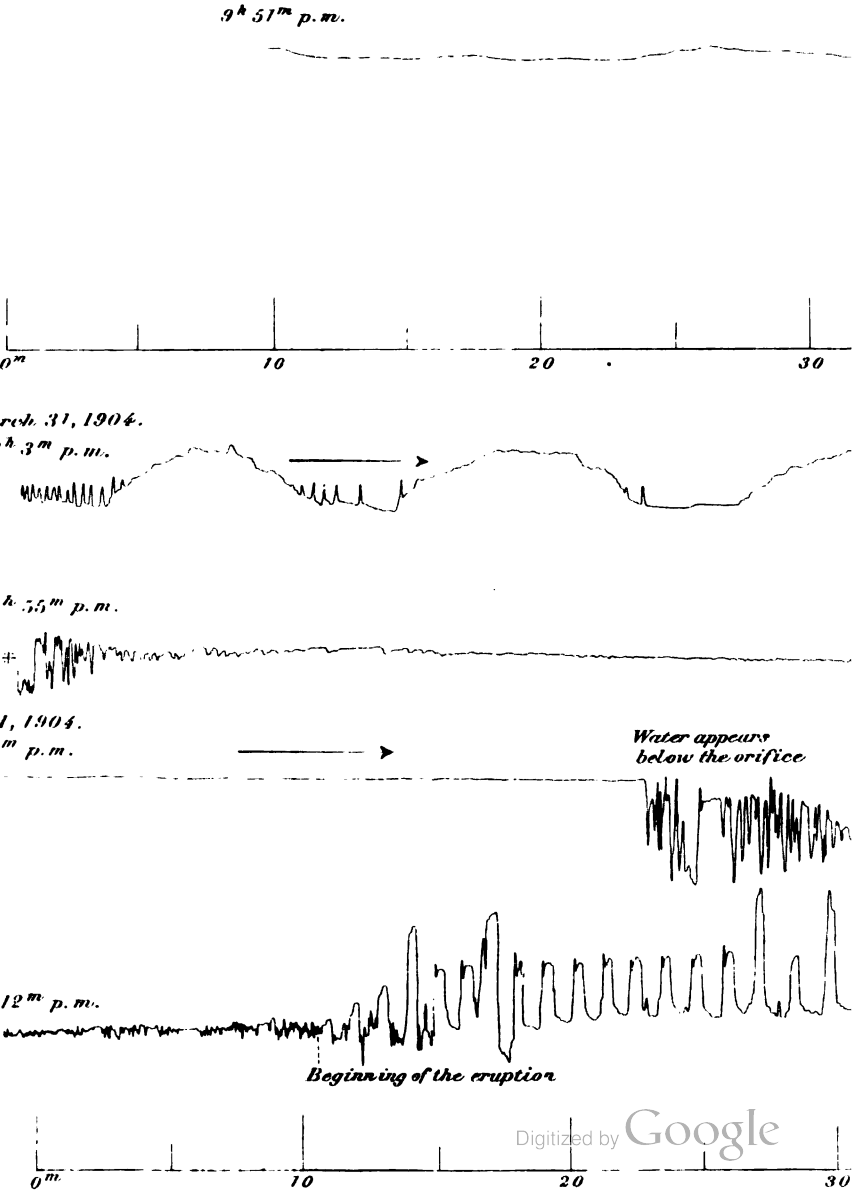


Fig. 5.



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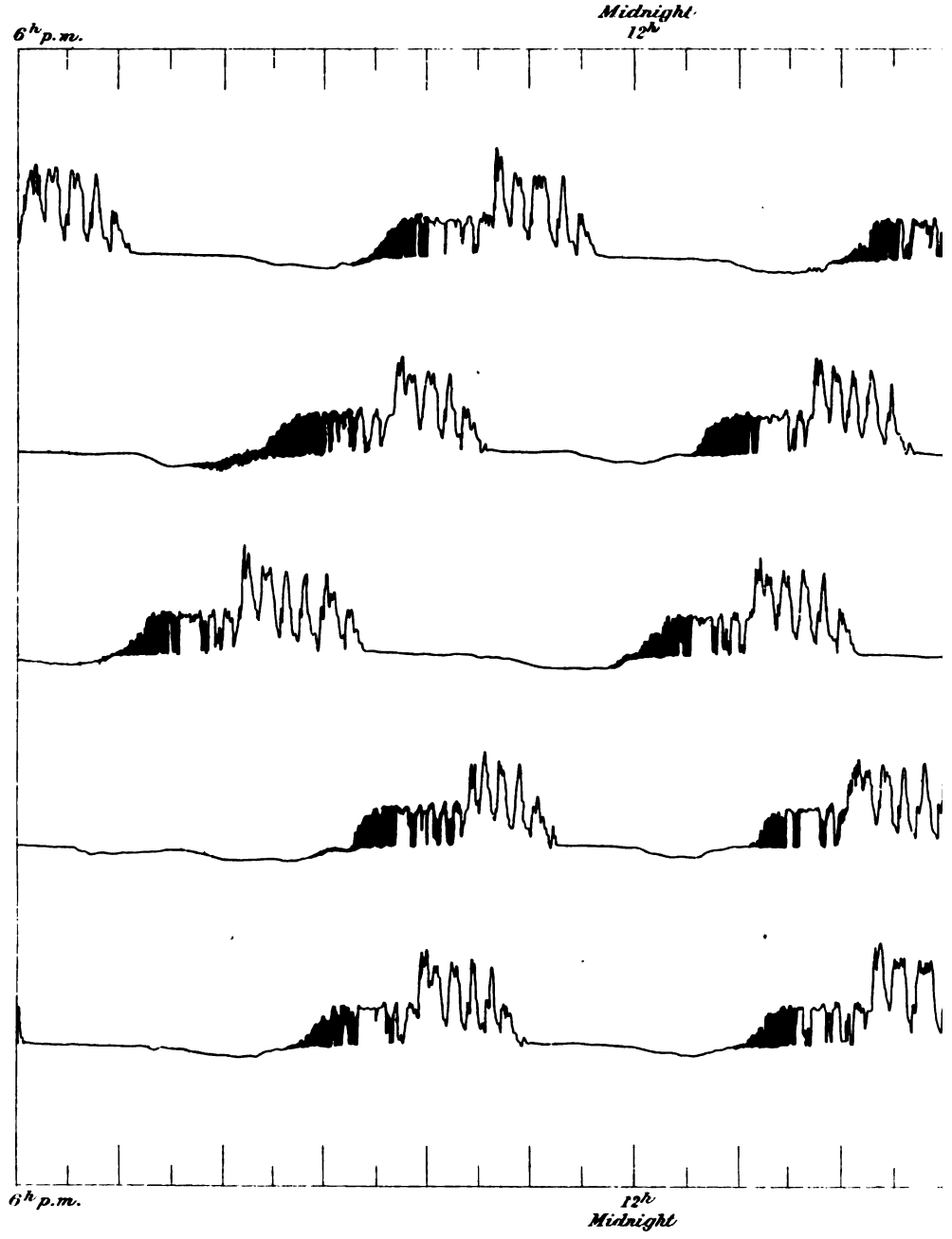

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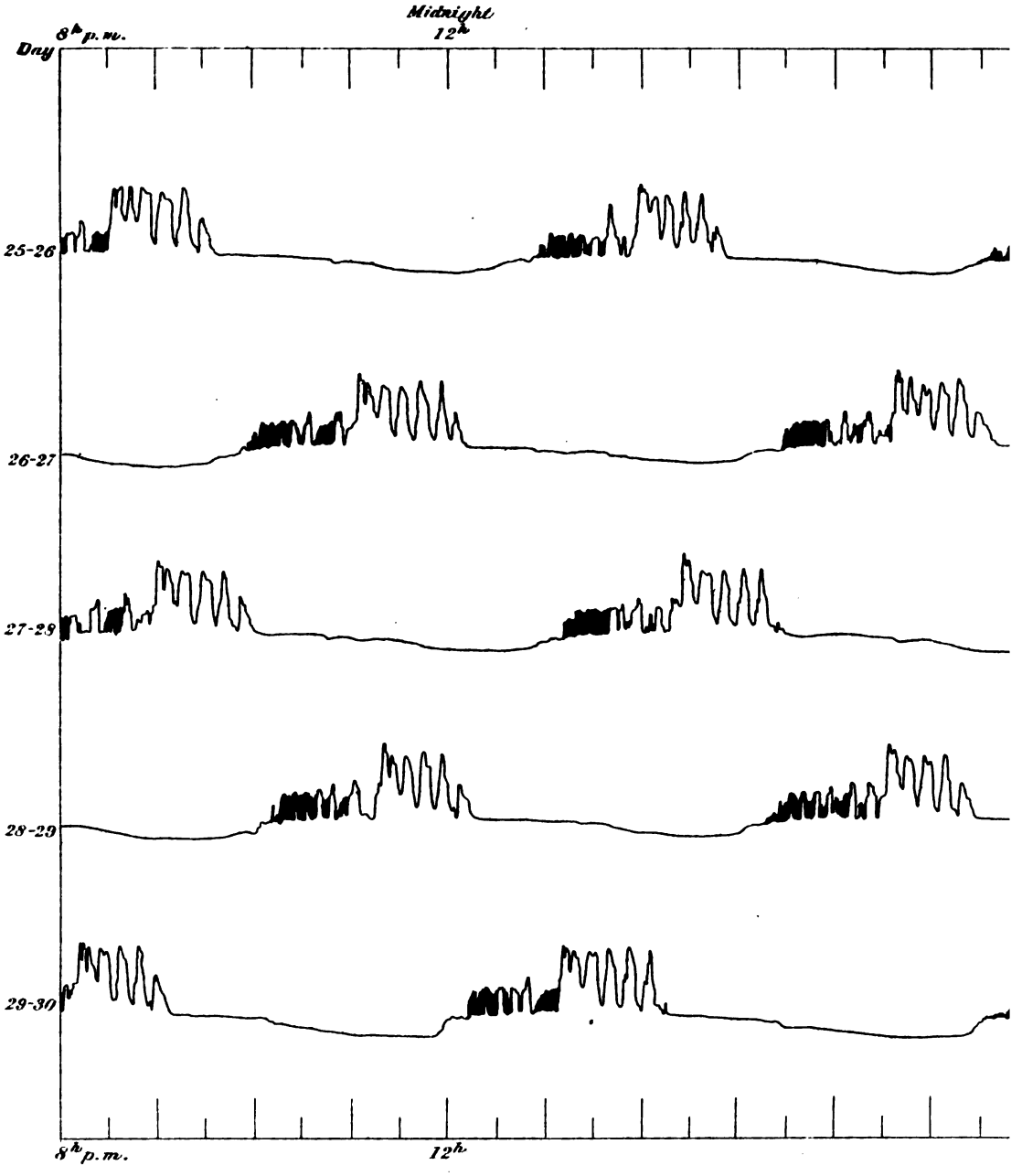

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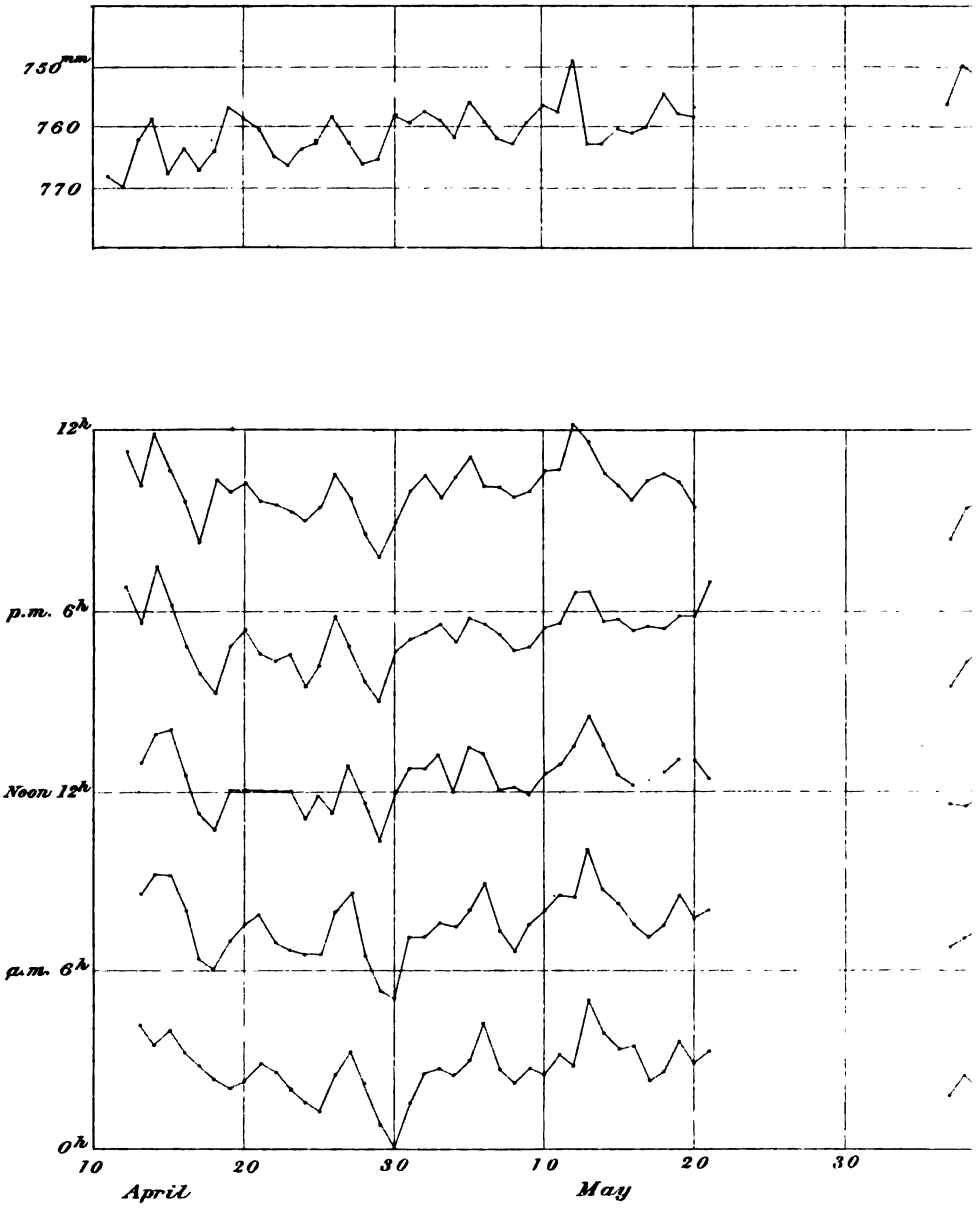

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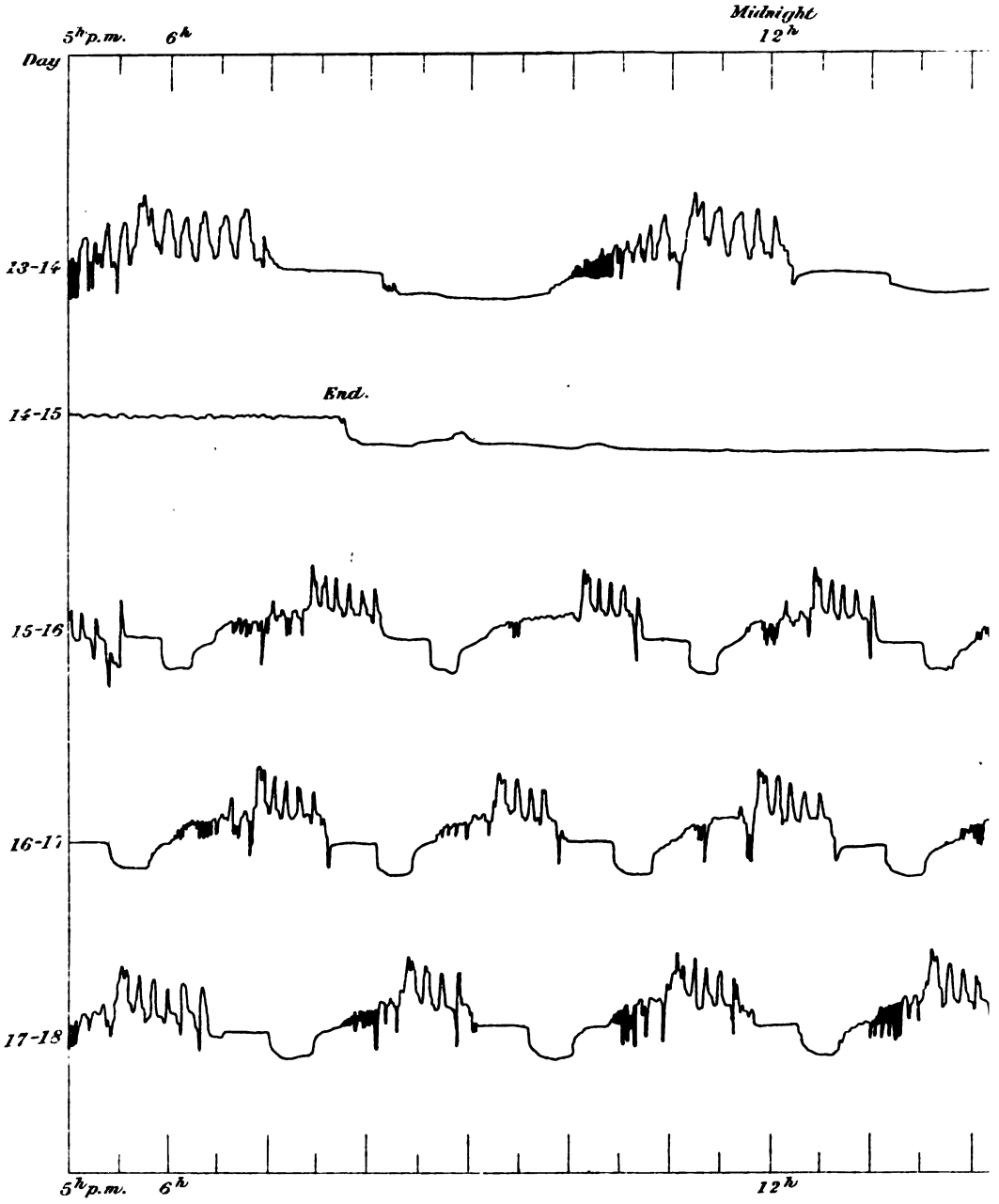

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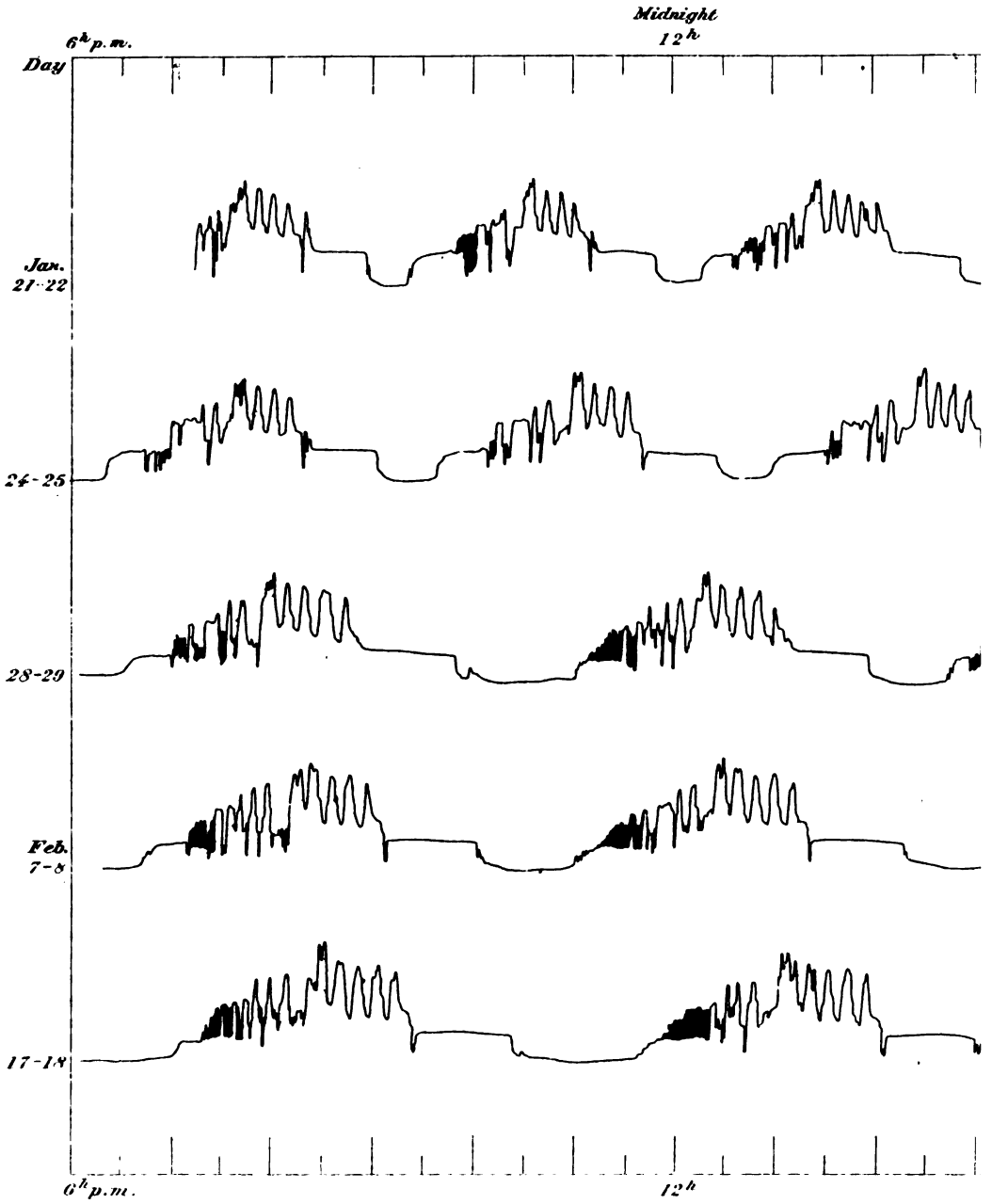

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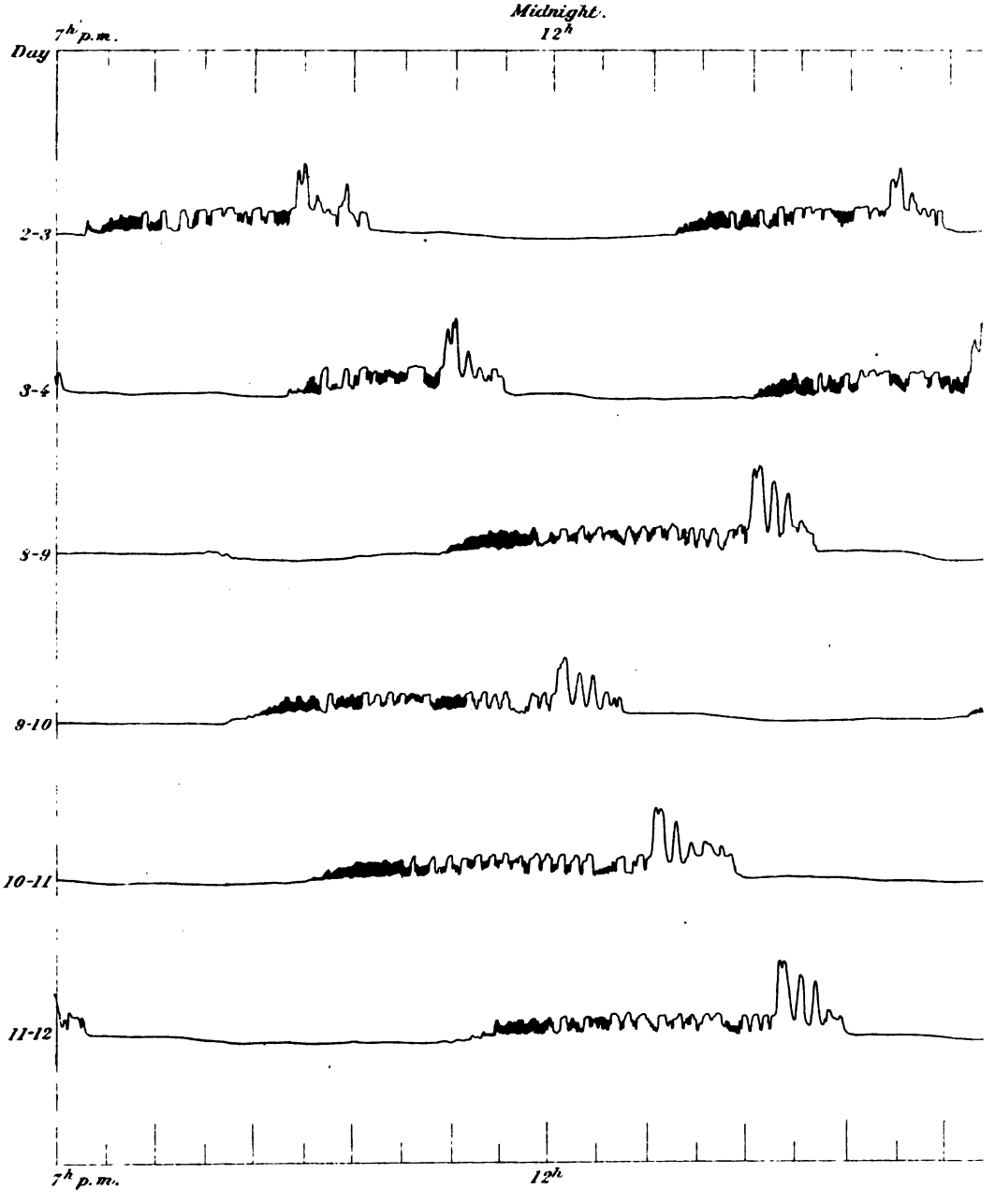

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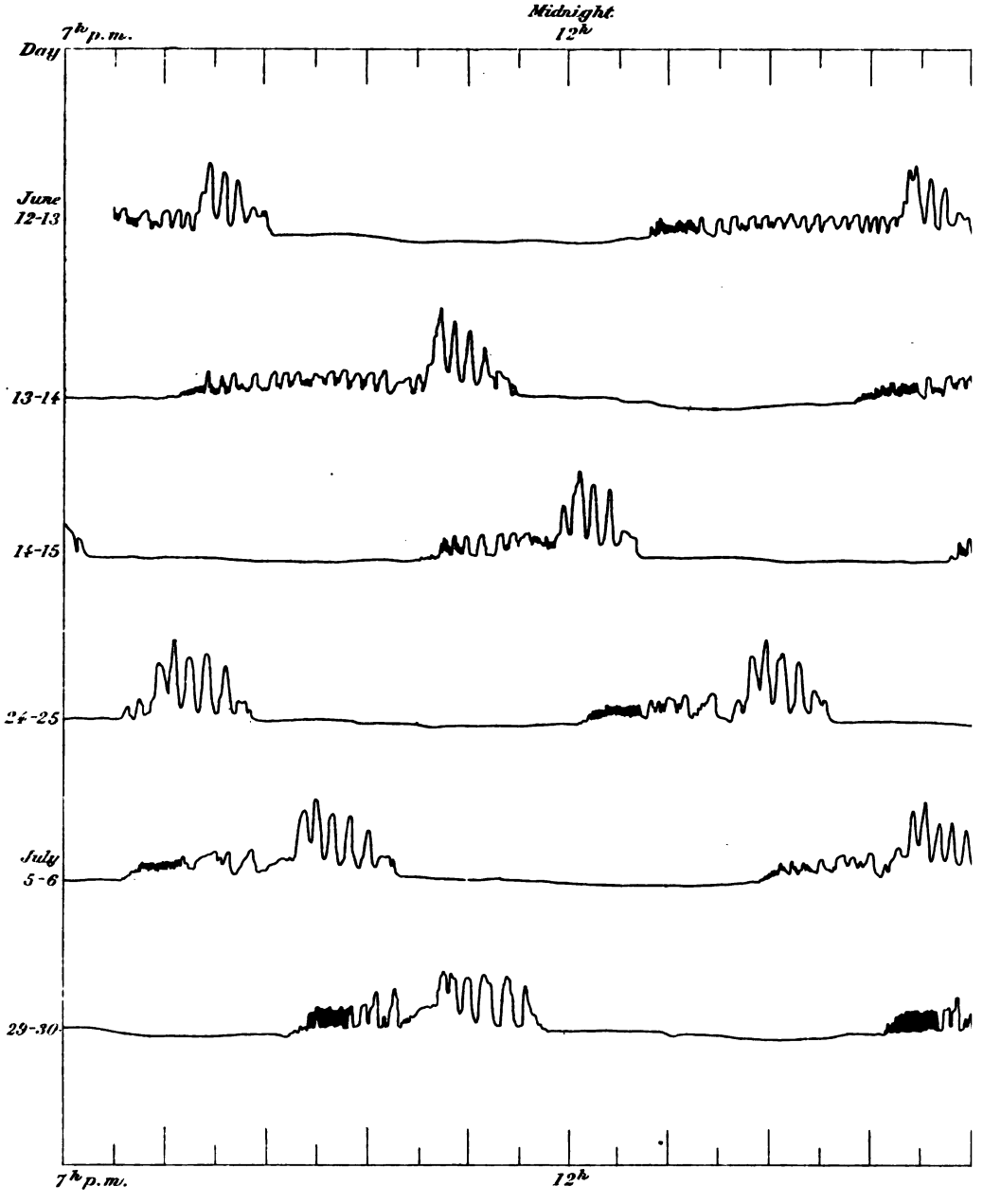

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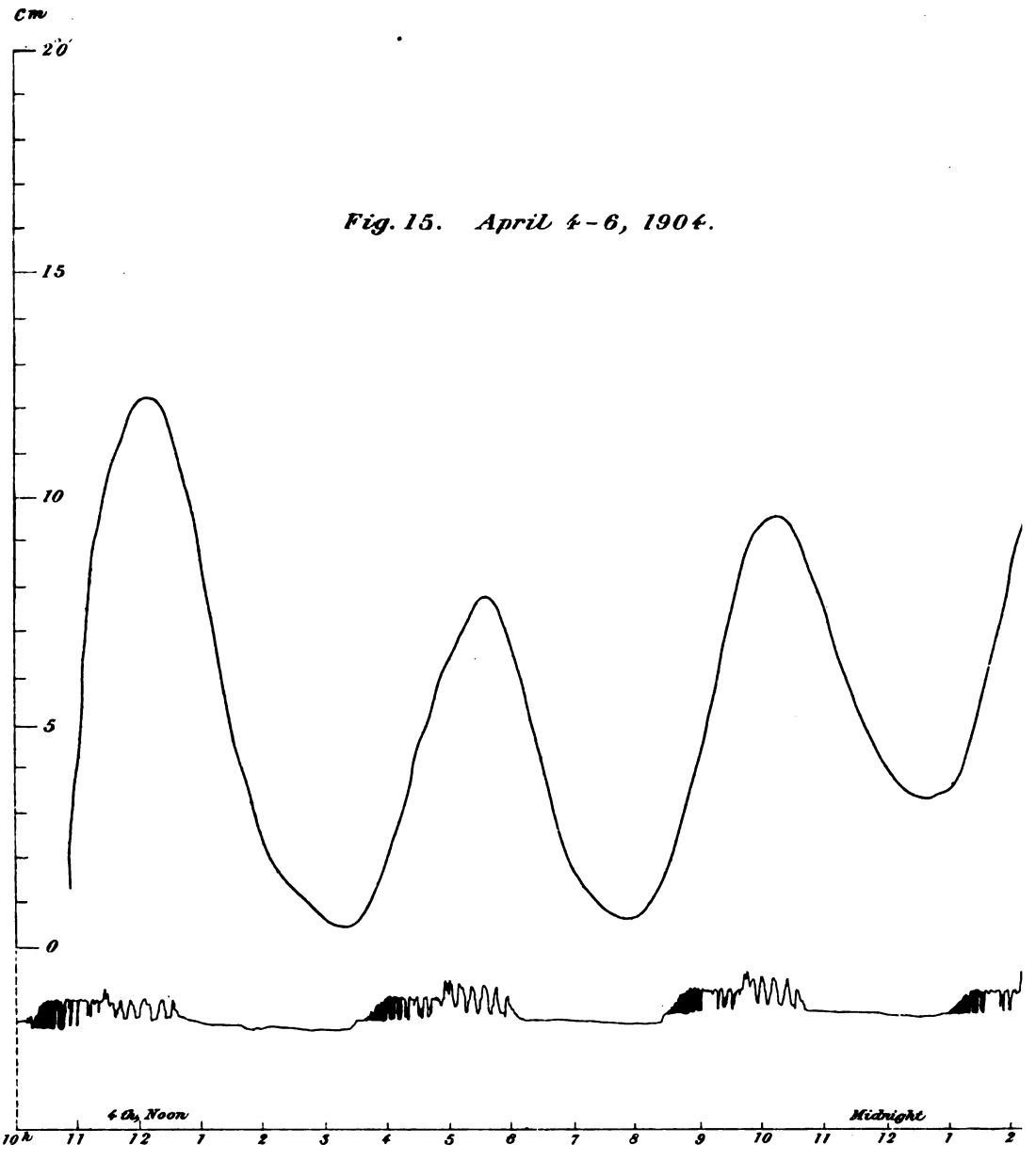

Fig. 15. April 4-6, 1904.

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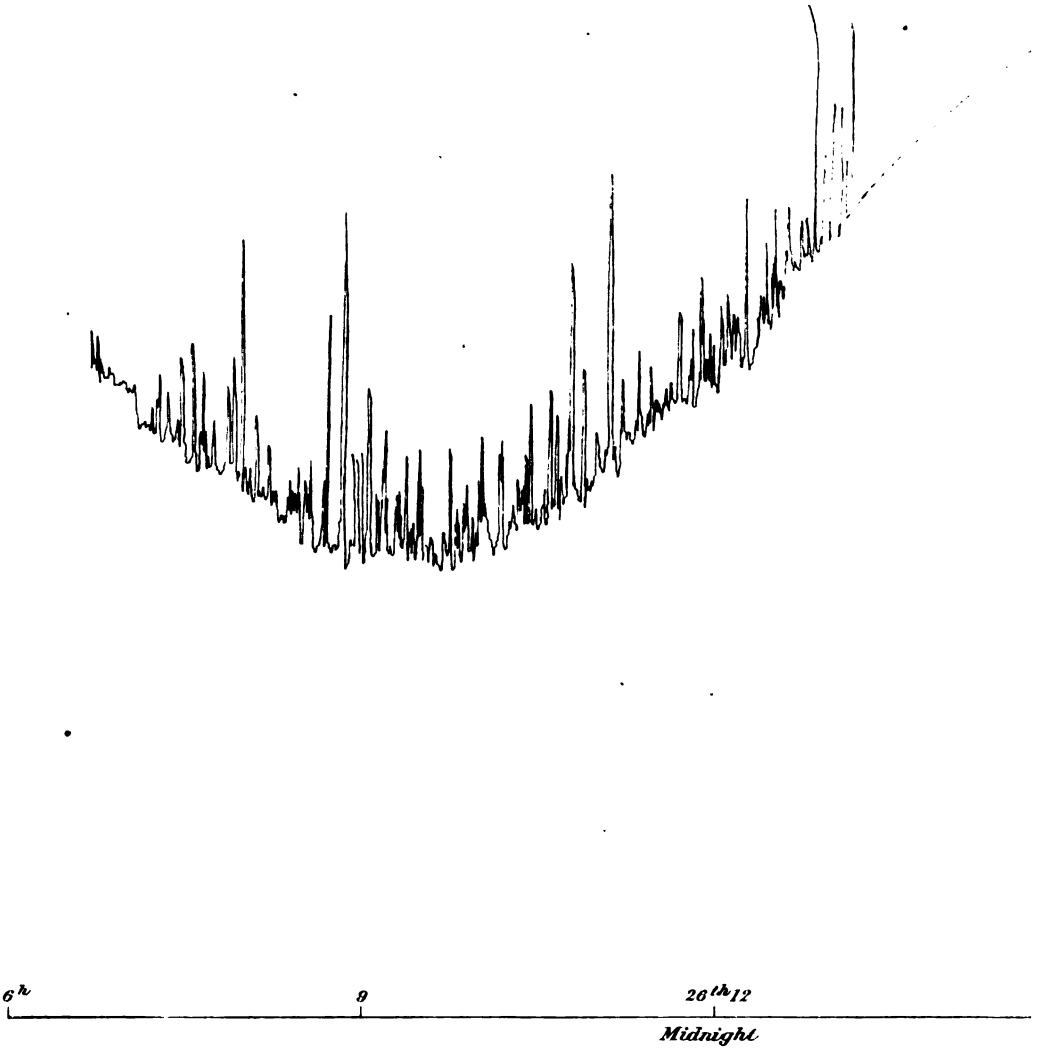

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PUBLICATION OF THE EARTHQUAKE INVESTIGATION COMMITTEE
IN FOREIGN LANGUAGES. No. 22. SECTION C, ART I.

The Ephemeral Volcanic Island in the Iwôjima Group.

By

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Asst. Prof. of Geology in the Coll. of Agriculture, Tôkyô Imp. Univ.

With Plates I–XII.

INTRODUCTION.

In the course of December 1904 (the 37th year of Meiji) a volcanic island was newly formed in the vicinity of Minami-Iwôjima which is situated at the southern extremity of the Fuji volcanic zone. The news was first reported in February of last year (1905) by some inhabitants of Iwôjima, and, as is fresh in our memory, was for a while an absorbing question with the public. In June last, at the request of the Earthquake Investigation Committee, I proceeded to the said island by the *Hyôgomaru* with a view to make an inspection there. But when I came near, to my great disappointment, I found it impossible to set foot upon the island, since the greater part of it was already worn out, leaving above the water a low reef just on the point of sinking. Moreover, the sea then raging, prevented me even from approaching the reef and obliged me to return without attaining the desired end. And if the present report gives the reader an impression that it is a long way from satisfactory or complete, I hope these circumstances will offer an excuse for that. Here I must express my heart-felt gratitude to Prof. Kotô who was kind enough to give me several valuable suggestions in studying my collected specimens, and without which, I fear, my report might have fallen still farther short of the mark.

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The New Island was nothing more than a submarine volcano, heaved up above the level by eruption, and was situated about 3 nautical miles northeast of Minami-Iwôjima. It may safely be inferred from its position, that this submarine volcano was one of the Iwôjima volcanic islands representing part of the so-called Fuji volcanic zone; and for this reason it appears convenient to make a statement respecting the present volcanic islands of Iwôjima or Sulphur Island group before entering into the main question.

IWÔJIMA GROUP.

The volcanic islands of Iwôjima group, also called Volcano Islands (Plate I) comprehend three volcanic islands ranged nearly north-south between 141° and 141° 30′ east longitude and between 24° and 25° 25′ north latitude. Of these three islands the central one is the largest and bears the name of Naka-Iwôjima[1] or simply Iwôjima (Sulphur Island); the one to the south Minami-Iwôjiwa (San Augustino Island), and the one to the north Kita-Iwôjima (San Alessandro Island). Kita-Iwôjima is situated 90 nautical miles southwest of Hahajima (Hillsborough Isl.) or 660 nautical miles distant from Yokohama, and Minami-Iwôjima, which is the southernmost limit of the Empire in this direction, is 740 nautical miles from Yokohama.

1. Kita-Iwôjima (San Alessandro Isl.)

Kita-Iwôjima is situated 25° 25′ north latitude and 141° 16′ east longitude. It is a volcano standing 2534 feet above the surface of the sea, about 12 km. in circumference, and 545 hectare in area. The coast line has become known in some measure, from the survey effected by Mr. Okamoto and others in 1904, but the topographic survey of the interior has not yet been made.

Fig. 1, Pl. II. is a topographic map of the island drawn from the survey made by Mr. Okamoto and from my own sketches. It will be seen therefrom that the outline of the island is nearly elliptical

1) Naka-Iwôjima means Middle Sulphur Island.

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with no remarkable irregularities of coast line. The mountain is generally precipitous, and the summit is divided into two prominent peaks, north and south. The one to the south is the higher (2534 feet) and its top, being nearly always covered with dense clouds, is said to be rarely visible from its foot. In consequence, it is not yet certain that this summit has any hollow vent as seen in most volcanoes. However, besides the two above-mentioned peaks, there is a somewhat low isolated one to the northeast of the south peak, and the deep valley skirted by this low peak and the north and south peaks has a white-decayed precipice in the middle part, as if influenced by solfataric action, suggesting the trace of explosion crater.[1)]

The mountain sides are very steep and directly lead to the sea without leaving any coastal plain around the island. Along the shoreline, however, there is a gravel beach of from 80 to 100 meters wide, with scattered big pebbles. It is a very noticeable fact that at the distance of about 100 meters from the water's edge the sea is very shallow, being only 2 or 3 fathoms deep, and even a small boat cannot approach the shore easily, owing to the waves usually raging there.

This submerged platform, or wave-cut terrace, together with the said gravel beach along the shore, marks the space which the water has conquered by dint of wave-cutting, since the formation of the island. Moreover, the steepness of the mountain sides (far steeper than the inclination of lava or tuff strata composing the volcano) must also be attributed to this rapid wave-cutting as well as the rapid formation of sea-cut cliff, for in such cases erosion plays a more important part compared to weathering which generally tends to reduce the angle of the slope; and the more resistant the material, the steeper the slope of the mountain, as is the case with Kita-Iwôjima.

Our landing and inspection being confined to the small sphere of Higashi-Ishinomura and neighbourhood on the eastern coast, I must confess that I could not obtain sufficient materials to show the geolo-

1) The position of the supposed exploration crater is shown by a dotted line in Fig. 1, Pl. II.

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gical construction of the island. But, so far as I could observe, the greater part of the mountain is composed of a comparatively hard kind of volcanic agglomerate containing a sheet of lava, which is cut in every way by dykes of dark-coloured andesite. In the precipice along the shore, about 200 meters south of Higashi-Ishinomura, there are exposed four or more dykes of great dimension, some reaching about 300 meters in length, the grand appearance of which can be seen from the far distant sea (Fig. 2, Pl. II.).

(i) *The agglomerate-forming augite-andesite* is a hard and somewhat vesicular rock which contains abundant phenocrysts of feldspar in dark gray-coloured ground-mass. Its external appearance greatly resembles the agglomerate-forming andesite of Hahajima which is seen alternating with Nummulite-tuff. Under the microscope, it is found to be of holocrystalline-porphyritic structure, containing phenocrysts of plagioclase and altered augite (Fig. 3, Pl. IX.). The plagioclase, though it is fresh and transparent, contains in inclosures a small quantity of augite besides magnetite and some glassy substances. These inclosures are arranged zonally along the cleavage face of the plagioclase. Polysynthetic twin of albite type is very common and pericline twin is also occasionally found. Considering that the extinction angle at *P* face reaches even $-37°$, it is safely inferred that it belongs to the most basic anorthite. The porphyritic augite is usually altered into a bastite-like substance of greenish brown or yellowish brown colour, with dark secreted grains perhaps of magnetite on its peripheries and cracks. The same phenomenon presents itself in the agglomerate-forming augite-andesite of Hahajima. The ground-mass is composed of lath-shaped plagioclase, augite grains and magnetite, with no trace of glass-basis.

(ii) *The Dyke-andesite* is a porous dark gray-coloured rock of basaltic appearance. Those marginal parts which are in contact with agglomerate are especially glassy and abounding in pores. As phenocrysts there exist a great number of plagioclase and a

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very few of augite, but no olivine. The plagioclase is transparent and full of glass inclosures, and polysynthetic twinning of albite type well developed in it. The wide extinction angle shows that it is of soda-lime feldspar of basic composition. The augite is of light yellow-gray colour and weak pleochroism, with well-developed prismatic cleavages. The ground-mass is of hypocrystalline structure and is composed of microlites of plagioclase, augite and magnetite, with a small amount of some glassy substances. The pores of various sizes which exist in the rock are generally fringed with yellow oxide of iron (Fig. 4, Pl. IX).

Though the whole island except the southern side (with its steep inclination) is covered with a thick forest, the trunks are all short on account of the strong sea-wind which prevails. Only near the beaches and in the valleys less exposed to wind, tropical trees of evergreen broad leaves, such as Calophyllum inophyllum *L.*, Terminalia Catappa *L.*, Hibiscus tiliaceus *L.*, Hernandia peltata *Meisn.*, &c. are seen in comparatively good growth. Slow inclining talus places in the island, such as the neighborhood of Higashi-Ishinomura, are thickly covered with red laterite, and there sugar-canes, maize, sweet potatoes, gingers, etc. are cultivated. On the beach and the talus ground above mentioned, decomposition of soil is complete and no substance which bears any sign of recent eruption is to be found. This, to my mind, goes to prove that the island lost its activity long ago, in which respect it resembles Minami-Iwôjima and widely differs from Naka-Iwôjima.

I may add here that this island, like the other two, had been long uninhabited, till, in 1899 Mr. Ishino, an inhabitant of Hachijôjima, set his hand to the reclamation. Since then, the population has increased year by year, so that at present there are 36 families and 178 inhabitants in the east and the west Ishinomura.

Submarine Volcano near Kita-Iwôjima.

At the distance of about 3 nautical miles northwest of Kita-Iwôjima there is a submarine volcano. Once it emitted steam and

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displayed a very grand spectacle.[1] With the earthquake of 1889, the emission came to an end, but a shoal covering the space of about 2 miles from north to south still remains to mark its site, where the sea-water is always found muddy and disturbed.

2. *Iwôjima* (*Sulphur Island*).

This island, situated in the centre of the Iwôjima group, is the largest of the three sister islands.[2] It was discovered, along with the north and south Sulphur Islands, in the year 1784 or thereabouts, by Captain Gore who, after the death of the famous explorer Captain Cook, explored the Pacific Ocean on board the *Resolution*. As Captain Gore christened it Sulphur Island it bears the name of Iwôjima, but has come to be called Naka-Iwôjima, viz., Middle Sulphur Island in distinction to the north and south Iwôjima.

This island is like a gourd in shape, extending from southwest to northeast. It is more than 24 km. in circumference and 1895 hectare in area. Except at the neck, the island is surrounded by precipices facing the sea. The coast-line of the island, together with that of Kita-Iwôjima, was made known by the survey of Mr. Okamoto in the year 1904, but the relief of the interior has not yet been ascertained. Fig. 1, Plate III is a topographical map drawn on the basis of the contour of the island by Mr. Okamoto, to which I have added contour lines with the assistance of my own sketches and investigations of part of the island. From a scientific point of view, the construction of this island is of great interest. There stands a low tuff-volcano called Motoyama, which occupies the greater part of the island, in the southwestern extremity of which rises a cone-shaped volcano called Suribachiyama or Mount Pipe. These two volcanoes present a peculiar contrast, the sight of which is very impressive. Fig. 2, Plate III shows the view of the island in the southeastern direction from Nishiminato, the anchorage of regular

1) A sketch at the time of its activity is shown in a chart.

2) 24° 28′ north latitude and 141° 13′ east longitude.

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liners; Fig. 3[1] shows the view of the island due east on the way from Nishiminato to Minami-Iwôjima; and Fig. 4 is a distant view from the southeast. This last figure is drawn from sketches by the late Prof. Y. Kikuchi, who visited the spot in 1888. A comparison of these three figures will make it easy to picture the topography of the whole island. In natural features, as mentioned above, Naka-Iwôjima is of a unique character and no doubt the most interesting member of the Iwôjima group; but unfortunately we had not time for a close examination, spending only a few hours in inspecting a part of Motoyama. As regards Mt. Pipe, we had no opportunity of climbing it, and it is a matter of great regret that I cannot make a full report of this interesting volcanic island. We have, however, a report published in the "Tôyôgakugei-zasshi"[2], by the late Prof. Y. Kikuchi who landed the island and inspected more especially Mt. Pipe. Again, Dr. Johannes Petersen published, in his "Beiträge zur Petrographie von Sulphur Island, Peel Island, Hachijô and Miyakejima" (1890), a short report of Dr. Warburg (who visited and collected rocks there in 1887) together with a detailed account of his own microscopic investigation of the rocks. Although Motoyama occupies 96% of the whole island, it is a low plain hill only about 430 feet high above the sea and 200 feet lower than the Pipe; and it is entirely composed of yellow tuff, with no trace of lava-flows. Indeed, such another pure tuff-volcano is not found in any other parts of our country's possessions.

Motoyama-tuff is a light friable pumiceous tuff of pale yellowish red colour, the greater part consisting of decomposed pumice powder. Of this tuff, two different kinds may be recognised: one is fine-grained and homogeneous with minute black spots, and the other is somewhat coarse-grained, so that the component pumice fragments can be clearly observed with the naked eye. The latter is usually found forming a thin layer in the former.[3]

1) Mt. Pipe is seen near in front.

2) A scientific journal written in Japanese. Kikuchi's report appears in No. 77 of this journal.

3) The former was mentioned by Dr. Petersen as tuff.

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On pounding these two kinds, washing off the clay part produced by decomposition of pumice, removing the magnetite[1] from the remaining sand, and then separating them by Thoulet's solution, it was found that there existed no distinction between them in point of mineral composition; that is to say, the minerals were apatite and monoclinic pyroxene that were separated by dense solution, the specific gravity of which was from 2·8 to 3·1.

The apatite is of a colourless transparent long prismatic crystal of very distinct outline. It is often 1 mm. long and is composed of ∞P, P and rarely oP. What is most wonderful in it is the glass-inclosures, which often assume the form of parent mineral after the style of negative crystal. Most of them contain immovable bubbles (Fig. 1, Pl. XI). Inclosures are occasionally light brown, but generally colourless, some with a dark opaque substance in one part. Dr. Petersen says that some of the inclosures are liquid.

The monoclinic pyroxene is generally separated in irregular broken pieces. It is fresh and sharply edged, and is composed of ∞P, $\infty P\bar{\infty}$, $\infty P\breve{\infty}$, P and rarely oP. The pleochroism is uncommonly conspicuous and varies between c smaragd-green, b olive-green and a grayish green. $c : c$ in the symmetrical plane varies from 50° to 54°. It contains a great quantity of acicular apatite, magnetite and glassy substances in inclosures.

The feldspar may be separated by a solution of from 2·5 to 2·37 specific gravity and is obtained in cleavage slices or in irregular broken pieces. It is in most cases decomposed, and some of the pieces are covered with colourless micaceous scales, nearly hexagonal with round margins and with a gray-coloured spot in each centre, as shown in Fig. 4, Plate XII, or partly altered into clayey substance. Dr. Petersen infers this feldspar to be orthoclase from the absence of twin laminae and from the

1) Magnetite occurs in great quantity in octahedral crystals or in irregular grains.

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optical orientation on *P* and *M*; but, besides this questionable orthoclase, twinned feldspar unobserved by Dr. Petersen can be found in considerable abundance. This twinned feldspar is in all probability oligoclase as judged by optical relation. It contains brown and colourless glass with gas bubbles and apatite needles in inclosures.

In short, this rock is of an entirely different nature from those ejected from the Pipe with respect to the nature of its augite and feldspar, and the absence of olivine; neither does any relation seem to exist between the rock in question and those of the New Island with the exception of the resemblance of the apatites.[1]

As has already been said, though Motoyama-tuff is uniform in texture, yet some coarse-grained parts are imbedded everywhere; so, as a whole mass, it clearly presents marks of bedding, and the whole stratum descends obliquely in all directions, dipping slowly from the central part of the mountain. This stratum towards the sea assumes a terrace-like form, with precipices presenting remarkable traces of wave abrasion.[2] The flights of these terraces, of tuff consolidated at the sea-bottom, terminating in the afore-said manner or found in the form of "Tischstein," are shown in Fig. 2, Plate VI. The formation is a relic of abrasion, and is a clear proof of the upheaval of ground in Motoyama. I have also discovered two other wonderful facts strongly confirming my inference. One is that, as is shown in Fig. 1, Plate VI, at the height of some 430 feet in the mountain, madrepore corals cluster together here and there, forming thin coral reefs, most of which belong to the living Stylophora species (Plate VII). These coral reefs struck me with delight when I found that they bore very little mark of weathering, still retaining their life appearance though blackened on their surface, and standing in bold relief upon the tuff. This goes to show that the elevation of the

1) Compare Fig. 1 and Fig. 2 in Plate XI.

2) Vid sketches of Plate III.

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volcano is of much later occurrence than is generally supposed. The other fact is that, together with these coral reefs, many tuff-pebbles, which assume the round flattened form so characteristic of a surf-beaten beach, are found everywhere on the mountain. Thus there is no room for doubt that this island was formed with suddenness not long ago, and from this fact it is also clear that the tuff of Motoyama is a sedimentary deposit of the sea-bottom.

I may here add that according to some inhabitants who immigrated here some years ago, the land is still uprising, most conspicuously so at the neck, east of Mt. Pipe. Its northern shore was formerly the anchorage of vessels which visited the place, but owing to the gradual rising of the sea-bottom, it ceased to afford shelter for vessels, and mariners have been obliged to choose Nishiminato instead.

Thus we see it is of comparatively recent occurrence that the whole mass of Motoyama volcano was elevated above the surface of the sea; but the formation of tuff on the sea-bottom is no doubt anterior to that of Mt. Pipe, as will be proved below. Since the formation of tuff, Motoyama has gradually diminished in activity, till at present it has only about ten solfataras on the top. As is shown in the topographical map in Plate III, the solfataras are scattered in a comparatively large area; moreover, each solfatara seems to have had its own fate, and frequently changed its position. It may also be inferred by the presence of the above-mentioned corals in their midst that some of these solfataras were produced after the appearance of the volcano above the surface of the sea. Among these solfataras, the central Motoyama-solfatara and Furuyama-solfatara about 150 m. north of the above are ejecting sulphurous vapours in the greatest abundance at the present time. Again, on the shore of Nishiminato, the only landing place of the island, a hot spring is said to be seen.

It is a fact no less noticeable that the entire surface of Motoyama is covered with volcanic sand or lapilli varying in size from a rice-grain to that of a pea. These volcanic sand and lapilli are com-

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posed of various volcanic ejectamenta, such as black obsidian, spongy pumice, reddish lava scoriæ, dark-coloured lava fragments with phenocrysts of feldspar and isolated feldspar crystals, etc. They are evidently not from Motoyama, but from Mt. Pipe, seeing that the petrographical nature of the sand bears no resemblance to the ejectamenta of the former but is similar to those of the latter, and bigger grains are found in greater quantities as we approach Mt. Pipe. Dr. Warburg and Dr. Petersen were certainly mistaken in surmising that feldspar crystals and other ejecta had been separated from Motoyama-tuff by weathering.

The most interesting of these volcanic sands is the crystal bomb of feldspar coated with a thin crust of black glass, some samples of which are so large as to reach 15 mm. in length. The crystal habit is tabular owing to the development of *M* face, and in most cases two or three crystals penetrate each other obliquely, thus forming a kind of twin. The surfaces of the crystals are generally rough, and both their angles and edges are worn and more or less rounded, though not utterly obscure. In them *M* is best developed, *P*, *T* and *l* are in narrow belts, and Carlsbad twin is invariably developed. From their extinction angles which are $-1°$ on *P* and $-5°$ on *M*, it may be inferred that they are of a kind of andesine. The crystals, though quite fresh, are full of yellowish brown glass-inclosures which are arranged zonally along the cleavage-face. In these respects, they bear affinity to the feldspar in the pumice of the New Island.

As mentioned before, this feldspar sand is generally crusted with a thin black glassy coating; even where part of the coating is worn out by weathering, a sponge-like glass still remains glittering in the reentrant angle of the crystals. This glass coating is very similar to the ground-mass of glassy andesite forming part of Mt. Pipe, from which we see that this feldspar sand, as is the case with the anorthite bomb at Miyakejima[1] already studied by the late Prof.

1) On Anorthite from Miyakejima. The Journal of the College of Science, Imper. Univ. Vol. II.

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Kikuchi, was once floating in magma at the crater bottom of the volcano Pipe, and was ejected together with other volcanic sands during the subsequent eruptions. Thus the feldspar bombs in these two places—one andesine and the other anorthite—are different in composition and crystal habit, but the same in the manner of ejection. It is an interesting fact that similar feldspar bombs are also found in Ôshima and Hachijôjima, so that this phenomenon seems to be characteristic of the Fuji volcanic zone.

The volcanic sand mixed with feldspar crystals is found lying thicker on the ground as we approach Mt. Pipe, at some points reaching even the thickness of 10 or 12 inches. In the vicinity of the Pipe there are scattered lava blocks of various sizes and shapes, half buried in the sands. They are somewhat scoriacious and have tabular phenocrysts of plagioclase in the ground-mass of dark gray colour. Petrographically they are of the same quality as a kind of lava which composes the cone of the Pipe. The most noticeable thing about these lava blocks is that wind ablation[1] is very conspicuous in them, and is expressed in various stages: thus some of them have their exposed parts considerably erroded into a peculiar conical form whilst they almost keep their original form only in the lower parts buried in the sands; some have a crown-like top whilst they have the feet of their exposed portions greatly worn; and others have lost even their crowns through the influence of the wind, so that their surface is reduced to the same level as that of the sands.[2]

To conclude: Motayama is an elevated submarine volcano, which once ejected a great quantity of pumiceous ashes and formed the so-called Motoyama-tuff under water; soon after the formation of the tuff was completed, Motoyama became weakened in volcanic activity without effusing any lava, and at the same time heaved itself up at a rapid rate, until its top got to the height of 430 feet above the

1) The prevailing wind in the island is from the south.

2) cf. Journal of Geography (in Japanese), No. 202. "Geographical Trip to the New Sulphur Island" by Mr. Satô (*Rigakushi*).

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sea level. This upheaval of the mountain, be it remembered, seems to be still going on.

Suribachiyama or Mt. Pipe.—We found no opportunity of inspecting this mountain, of which, however, an exploration was made by both the late Prof. Kikuchi and Dr. Warburg.[1] The former's report appeared in the "Tôyôgakugei-zasshi" and the latter's in Dr. Petersen's "Beiträge", as before mentioned, and it is to these reports as well as Petersen's studies on rocks that I owe the following description of the structure of the volcano.

Mt. Pipe, entirely different from Motoyama in all respects, is a strato-volcano composed of ash layers and lava sheets. It forms a truncated cone, standing about 640 feet above the sea-level and 200 feet higher than Motoyama. As is the case with many volcanoes, it has in its top a crater in the shape of a bowl or the Japanese "suribachi"; hence the name. There are two crevices ejecting steam, one on the south and the other on the west side; and the former has a sublimate of sulphur, alum, gypsum and potassium salt. On the northern side of the crater a deep valley (perhaps barranco) opens upon the sea. Alternating strata of ashes and lavas are found sloping down from the crater on all sides. Prof. Kikuchi writes that the founaation of the volcano Pipe is a horizontal layer of gray sandy volcanic ashes, which is composed of glassy substance probably sedimented in the water (Fig. 5a, Pl. III). The professor, as it seems, considered that it was of the same origin as the so-called Motoyama-tuff, but, I must venture to say, there is not sufficient reason to believe in their brotherhood. Covering this fundamental ash layer, there are some lava beds, which form a precipice of about 100 feet in height (Fig. 5b, Pl. III), partly cracked into a vertical prism. It is these lavas that are mentioned by Dr. Petersen as *glasiger Augitandesit, Bimssteinartiger Augitandesit, Schwefelfuhrender Augitandesit,* &c. Most of them are in the form of black vitrophyric rocks, containing tabular crystals of plagioclase in a compact or porous ground-

1) loc. cit., p. 7.

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mass. Under the microscope, oligoclase, monoclinic augite, olivine, apatite and magnetite are recognizable. Of the ground-mass, some are hyalopilitic and the others glassy, all containing augite-microlites and other devitrified products. Those parts of the lava which were subjected to the influence of solfataric action are now bleached into white or light gray colour. Overlying these lava beds, and composing the greater part of the volcano, are gray ashes containing plagioclase, augite, olivine, magnetite, apatite, besides compact or pumiceous glasses, together with various decomposition products.

In a word, Mt. Pipe, very different from Motoyama, is a strato-volcano active until recent times. After the first ejection of volcanic ashes, hard lava-sheets were formed, which made the mountain solid and precipitous, forming itself into a truncated cone quite unlike that of Motoyama; and it is of recent occurrence that it ejected the above-mentioned feldspar crystals and various volcanic sands now covering the whole island.

Though we may assert that these two volcanoes entirely differ from each other in their structure and composition, we cannot say that they have no relation whatever to each other. Indeed, the fact that after throwing out volcanic ashes, Motoyama became inactive without any effusion of lava, may have been the result of the subterranean magma finding its own way, which culminated in the formation of the present strato-volcano of Mt. Pipe.

3. Minami-Iwôjima (San Augustino Island).

Minami-Iwôjima or South Sulphur Island is the southern-most of the three principal islands of Iwôjima group, and its geographical position is of 24° 14′ north latitude and 141° 29′ east longitude; being in about the same latitude as the middle part of Formosa.

This island, 3039 feet high, is a strato-volcano of a conic form and of the same type as the volcano Pipe in Naka-Iwôjima and the volcano of Kita-Iwôjima. The outline of the island is almost spherical and it is only 8 km. in circumference. The mountain sides are all

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very steep and slope precipitously to the sea with an inclination of about 40°, without leaving any level ground at the foot. The top is almost always invisible from the sea, being covered with dense clouds. (Fig. 2, Pl. V and Fig. 1, Pl. IV.)

The mountain sides are overgrown with small bushes down to the middle height, but below no vegetation is found and bare agglomerates and lavas rise above the ground at a dip of about 20°. Only the northeastern side with no verdure is entirely of rust colour from the ashes which, it is said, covered it, at the time of the eruption of the New Island.

This island has not been inhabited for a long time, so that our knowledge of it is very limited.

THE NEW ISLAND.

History of its Eruption.—This island, the exploration of which was the chief object of our trip, made its appearance in November 1904, 3 nautical miles northeast of Minami-Iwôjima. On approaching it, as mentioned in the Introduction, I found the greater part had already been abraded away, and lost for ever the opportunity of inspecting it in person, so that I am in no position to give any detailed account of its formation, and all I can now do, is to state my scientific inference on the subject from the report of an exploration effected by some inhabitants of Iwôjima soon after the eruption. The following is a translation of some extracts from their report (in Japanese):

"A noise like the roaring of a cannon was heard from the south of Iwôjima on and after November 14th, the 37th year of Meiji (1904).

On the 28th of the same month, at 8 p.m. a feather of smoke was seen about 3 nautical miles east of M.-Iwôjima. At first, we thought that it was the smoke from a man-of-war at sea, and it was about an hour later when dark smoke came to be seen hurled up in greater quantities that we realised the cause of the phenomenon. That day, however, there was no such noise as had been heard before. After a while, the dark smoke changed its colour now

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into white and then into red, sometimes rising in full force and the next moment subsiding. At night, however, nothing could be seen.

On the 5th of December, we first caught sight of an islet lying amidst the smoke.

On the 8th of the same month, the said new island had the appearance of three smaller ones grouped together; but of-course it was not certain whether a group of three really existed or simply appeared to exist, owing to the presence of vapour brewed by the eruption.

On the morning of the 12th of the same month, the sky cleared up and the island made its full appearance. It was then single, looking somewhat higher in the eastern part, and level in the western.

On the 14th of the same month, the island assumed the appearance of a long one, at one time emitting white smoke and at another dark smoke from the middle.

On January 2nd of the 28th year of Meiji (1905), the island changed in shape growing higher in the western part, and emitting a little white smoke from the mid part. About 3 o'clock p.m., however, there burst forth voluminous dark smoke which was followed by white after twenty or thirty minutes.

On the 5th of January, the immigrants in Iwôjima met together and decided to attempt an exploration there and report its result to the island-office. When volunteers for the proposed adventure were called for, ten men responded, all determined to sail to the island in a boat and a canoe.

They commenced preparations on January 6th, and made several attempts to put to sea, failing each time on account of bad weather.

The weather becoming fine on January 31st, they at last succeeded in getting to M.-Iwôjima. This island being near the new volcanic island, nearly the whole surface was covered with ashes and the plants had all withered, except in a small part in the south-west. Much débris of pumice was found thrown up on the coast round the island.

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On the 1st of February, they sailed out from M.-Iwôjima and arrived at the New Island. The high waves on the shore made landing very difficult; moreover, as it was only a few days after the eruption, the party was exposed to great danger in the attempt.

* * * * * * * * * *

They then made a step survey and sketch of the island, and collected samples of stones. The island, as will be seen from the sketch in the appendage (Fig. 4, Pl. IV.), was about 3 miles in circumference, the highest portion standing about 480 feet above the sea. There was a small pond in the northern flank about half a mile in circumference, where vapour was rising profusely. In all probability it had been a crater. The north bank of the pond being only 3 or 4 feet high, the sea-water probably had used to run into the pond when high waves came. The south bank was precipitous and its highest portion formed the summit of the island. Though the island was composed of hardened rocks, the surface was all covered with loose ashes about 5 or 6 inches in thickness. It was about 200 acres in area and almost flat on the top, surrounded by narrow shore-plain 120 or 240 feet wide. * * * * * * "

The report of the immigrants above quoted tells us that they had heard sounds like cannon since the 14th of November—a very common phenomenon foreboding the coming eruption of a volcano; and it may be safely inferred that the vapour at the bottom of the crater was already growing active, its expansion causing the movement of the magma. At last the eruption began in earnest at 10 a.m. on the 28th of the same month with the bursting forth of smoke; and the island made its appearance on the 5th of December, though it changed its shape and the colour of its smoke very often. The white smoke showed that mere vapour unaccompanied by volcanic ashes was then being ejected, and the change of its colour into black or red told that volcanic ashes together with vapour had begun to be thrown forth in large volumes. As regards the changes in the shape of the island during its eruption, they may be accounted for by the con-

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jecture that, while large quantities of new ashes were accumulated at one point, those which had already been accumulated at another were blown away by explosions. In other words, the balance of these two controverting processes, constructive and destructive, must have determined the shape of the island. I feel still more confirmed in this conjecture when we consider that its centre of eruption seems to have changed from time to time.

What makes me more regretful than anything else is that we are unable to ascertain the component materials of the island, since no rocks were collected there, except pumice-débris which had been beached by the waves. It seems that these pumice-débris are part of what were effused in a lava-flow into the sea-bottom during the eruption and were broken off and thrown upon the beach by the waves. Mr. Azuma, one of the explorers, told me that what is mentioned as "rock" in the report, which formed the frame of the island, was of the same quality as the yellow tuff of Motoyama in Iwôjima. Though of course it is not to be believed that the rock was entirely of the same class as the tuff of Motoyama, at least it is evident that the New Island was not composed of any resistant hard lava. On examining the "ashes" which are described in the report as having covered the "rock" to the thickness of 5 or 6 inches, I found that they were a fine silt of light gray, or nothing but pumice in powdery form; and under the microscope, I also found them to contain the same plagioclase and augite as are seen in the pumice blocks collected. It is most probable that the New Island was constructed of loose volcanic products as is the case with many marine volcanoes, considering that the shape of the island often changed during the eruption, as mentioned in the report of the explorers.

The next subject which demands our investigation is the shape of the island. According to the report and the sketch by the explorers, the island was at first of egg-shape about 3 miles in circumference and 200 acres in area. The highest point, 480 feet above the surface of the sea, was in the northern part, which formed the big-

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ger end of the egg, the surface of the island slowly inclining toward the south (the dip being about 12° according to the explorers' sketch) with no ragged contours, while the northern is very steep, nearly vertical. Beneath this precipice, there was a long elliptical pond about 2400 feet in circumference, the northern side surrounded with a barrier only 3 or 4 feet high; and from some parts of the pond vapour was rising. From this fact, we may clearly conceive that the pond of the northern end was the centre of eruption or crater, that the island was but a portion of the crater rim appearing above the surface of the sea, and that the barrier bordering the north margin of the crater pond was of pumice-débris, drifted upon the island by the wind like those forming the beach round the island. The formation of such a pumice barrier was probably owing to the presence of a hidden reef forming a portion of the crater rim in the north of the pond. It is also obvious, from the explorers' report, that explosion had played an important rôle in the eruption of the New Island, that the greater part of the crater rim once formed there had been demolished by the explosion, and that the New Island was nothing more than that portion of the crater wall which remained free from the influence of explosion.

I believe that the pumice which was brought back by the explorers is part of the lava effused from the crater after its chief explosion. This may be proved from the nature of the lava which will be referred to below, as well as by the fact that the substance composing the body of the island was, as above mentioned, not rock of this kind, but loose volcanic ashes or tuffs. The vomited lava did not amount to such a large quantity as to form part of the island above the sea, and yet was sufficient to form a belt of gravel beach round the island with its broken pieces by aid of the waves. An enormous quantity of pumice fragments was also scattered about like shrapnel bullets by the eruption and carried away by the current to considerable distances, arriving at the Bonin Islands and even as far as the eastern coast of Honshiu and Riukiu Islands. In April 1906, I

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collected a number of pieces of drift pumice on the eastern coast of Awa Peninsula, of which the petrographic similarity with those of the New Island has been proved by myself by microscopical investigations. Also, according to the report of Dr. Nakamura, Director of the Central Meteorological Observatory of Japan, a great amount of pumice-débris arrived at the coast of Ishigakijima in Yayema Group, Riukiu, from the middle of May 1905 to the beginning of June of the same year.

Petrography of the Lava of the New Island.

(Olivine-augite-andesite)

a.) *Microscopic Features.* The samples given me for investigation are a dark brown vitrophyric rock, consisting of two different parts, obsidian and pumice. The former, as its pores increase, gradually passes into the latter, so that the manner of gradation is observable in one sample. Plate VIII is the photograph of one of these samples, the lower part being of obsidian, the upper part of pumice, and the middle of both in a transitional condition. Such an orderly transition of these two parts goes to prove that they were originally of the same lava. Perhaps the upper portion of the lava, which naturally comes in contact with sea-water, was consolidated into a sponge-like pumice on account of its sudden cooling, while the lower portion where the cooling must have been comparatively slow, was consolidated into compact obsidian. Under the microscope, no substantial difference can be found between the two.

1.) Obsidian Section.—It is of a brownish black colour and pitch-like lustre, and presents conchoidal fracture as is usual with this class of rocks. It bears comparatively large cracks, occasionally 3 mm. wide, looking as if cut out by a knife, besides smaller ones running across in every direction. These cracks, however, are comparatively shallow (none being deeper than 2 cm.), and confine themselves within the section of obsidian, never extending into that of pumice. The ends of the cracks are never sharp, but always dull.

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When the lava was about to cool and consolidate itself into masses in the water, large cracks were at once formed by the contraction of the masses, and no sooner were the walls of cracks suddenly cooled by the intrusion of sea-water, than the second cracks were produced, and so on. This may be clearly proved by the right angle at which the later-made cracks run to the surface of those which were made immediately before. If the cracks had not been formed, the obsidian would then have remained lying forever at the bottom of the sea and might not have come to our hands.

2.) Pumice Section.—It has a light brown colour, with somewhat silky lustre, and has large irregular pores, the greatest diameter o the largest one reaching 2 cm., besides smaller but deeper ones quite close to one another like those of a sponge. Both larger and smaller pores are generally lengthened at right angles to the surface of the boundary near the obsidian section, and turn in every direction at some distance from the boundary. But those forming a set go parallel to each other, as is seen in ordinary pumice. This is worthy of notice, because it is intimately related to the origin of pores. To my thinking, this is how the pores came into existence. When lava streamed out, the water in the molten lava turned into vapour, went up in innumerable bubbles, and formed viscous masses full of bubbles on the upper part of the flow. Thus, these masses of lava were consolidated into pumice in that condition. Larger bubbles were formed in the masses by accidental amalgamation of smaller ones, and subsequently consolidated into larger pores.

In the pumice section, as in the obsidian, tabular phenocrysts of feldspar and rarely small phenocrysts of augite and olivine can be seen with the naked eye. The feldspar is of a dull colour containing numerous glass inclosures, which are usually crowded in the middle of the crystal. The tabular form of the feldspar is very pronounced, owing to the development of brachypinacoid. Binary Carlsbad twin is not uncommon.

In the pumice section there is no sign of the presence of distinct

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cracks as in the case of the obsidian section, but this section is somewhat more easily fractured perpendicular to the longitudinal direction of its pores.

Some of the pumices which were abundantly found on the coasts of the Bonin Islands differ a bit in nature from that above mentioned. Prof. Kotô made microscopic examinations of some of these pumices, and found that they contain a great quantity of rhombic pyroxene rare in that of the New Island; from which it becomes quite clear that divers kinds of pumice arrived at the Bonin Islands. We can assume from this fact that there are frequent submarine eruptions at the bottom of the great ocean especially in the neighborhood of the Fuji volcanic zone, which escape our attention.

b.) *Microphysiography.* For the purpose of microscopic examination, I cut the obsidian section into thin slides, and treating the pumice section by Thoulet's solution, examined the two separately. This revealed to me that its mineral components were magnetite, apatite, olivine, monoclinic pyroxene, rhombic pyroxene and plagioclase (here named in order of individualization). These occur in phenocryst in the groundmass of light brown colour (Fig. 1, 2, Pl. IX; Fig. 1, 2, 3, Pl. X).

Magnetite occurs either in irregular grains or in cubic crystals with more or less rounded margins. It is often enclosed within other essential components, especially augites. This readily leads to the conclusion that it is the first of the individualization products. Apart from this no metallic mineral can be found.

Apatite occurs in prismatic crystals of a regular outline and its transverse section is hexagonal. It terminates either in P or in P and oP, and has a cleavage characteristic of this mineral crossing the main axis. It demands our special attention in this that it has glass inclosures of a light brown colour having the form of negative crystal as in the case of apatite in Motoyama-tuff. Many of the inclosures contain immovable air-bubbles (Fig. 2, Pl. XI.).

Olivine, though less than one fifth of augite in quantity, is found within almost every thin slide, and is separated together with augite

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and apatite, by means of Thoulet's solution of 3.1 or 3.2 in specific gravity. It does not exceed 2 mm. in diameter. The surface of the crystal is corroded for the most part, showing sections of imperfect square or of an utterly irregular outline. Observed faces are $\infty\bar{P}\infty$, $\infty\breve{P}\infty$, ∞P, $\bar{P}\infty$, oP, P, etc. It is characterized by its strong refracting power and its vivid polarization colour. Though it contains glass and apatite needles as inclusions, the quantity is not so great as in the case of feldspar, and there is rarely seen a pocket-like intrusion of glassy ground-mass as shown in Fig. 1, Pl. XII. It is always fresh and no trace of serpentinization is found.

Monoclinic pyroxene in phenocryst, is next to plagioclase in quantity and equal to olivine in size, occurring in short prismatic crystals surrounded by sharp margins, in which ∞P, $\infty\bar{P}\infty$, $\infty\grave{P}\infty$, $-P$ (or P) are found (Fig. 3–6, Pl. XI). Sometimes it is twinned on $\infty\bar{P}\infty$ (Fig. 7, Pl. XI). The colour is very characteristic, and varies between a yellowish gray, b and c yellowish green, though not distinct. The polarization colour is strong, and the maximum extinction angle on $\infty\grave{P}\infty$ measures 46°–48°. Prismatic cleavage appears in coarse lamellar sutures, besides other irregular fissures. Inclosures are very frequent. As in the case of olivine, glass with air-bubbles, apatite prisms of comparatively large size and magnetite crystals are the most common of inclosures. These inclosures do not run either zonally or centrally as in plagioclase, but some of apatite crystals and glass-inclosures lie parallel to some domal faces (Fig. 7, Pl. XI). This is rather singular. The deep intrusions of ground-mass may sometimes be seen, as is the case with olivine. Its specific gravity is about 3.2.

Beside the monoclinic pyroxene just mentioned, there are occasionally yellowish blue rhombic pyroxenes which exhibit parallel extinction Pleochroism is distinct, varying between c yellowish blue and a, b bluish yellow. Some of them represent hypidiomorphic relation with plagioclase.

Plagioclase occurs in tabular crystals on account of the large development of *M*, and the largest diameter sometimes measures 6 mm.

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towards the brachy-axis. It has four faces P, y, T and l, besides M; but y is sometimes wanting and r (?) seems to take its place. The outline is regular, usually fresh and transparent, but it contains plenty of acicular or short prismatic crystals of apatite and brown glass with air-bubbles in inclosures. Most of the glass-inclosures extend flat along the faces of basal or brachypinacoidal cleavage with edges parallel to a crystal face. In some cases they continue without interruption in a peculiar manner along cleavage faces as shown in Fig. 3, Pl. XII. Large crystals contain so many of glass-inclosures that the plate about 1 mm. thick can hardly transmit light. Thus large crystals usually present a dark gray colour to the naked eye. Even in such crystal as abounds in inclosures, the inclosures crowd the centre, leaving a narrow transparent zone in its periphery. In this transparent zone only a few rows of glass-inclosures run parallel to the crystal face, and many lines of growth can be seen. The twin-lamellæ of albite type can clearly be observed in the section of P–y zone or in the cleavage slice along P face. In large crystals, twins of Carlsbad type are commonly developed, but no pericline twins are seen. Extinction angles on P and M in a cleavage slice are on the average of $+1.7°$ and $+7°$ in Schuster's meaning respectively. This number shows that the plagioclase is oligoclase near $Ab_{78}\ An_{22}$ (Fig. 3, Pl. X.).

Ground-mass is composed of glass of light brown colour. Fluxion structure is indistinct, and no kind of crystallites could be seen. Nevertheless, it is of special interest that the quantity of microlitic prisms of monoclinic pyroxene (Fig. 5, Pl. XII.) are irregularly scattered. The largest of these augite-microlites is $\frac{1}{5}$ mm. long and $\frac{1}{20}$ mm. wide, and the smallest does not reach $\frac{1}{50}$ mm. in length. The longitudinal section is rectangular, and each end of it always curved and often indented. The indentation rarely runs deep into the crystal, partly in the form of glass-enclosures. The cross section is octagonal or square. What is most interesting in it is that two or more crystals by intersecting each other form penetration-twins of the shape of

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the letter X, of a cross or of a wheel. A few examples are illustrated in Fig. 5, Pl. XII. It is of light yellowish green colour with no pleochroism. The largest extinction angle is 52° to the main axis. These little augite crystals are not found in enclosures even in feldspars which are of later crystallization than porphyritic augite and undoubtedly belong to the second phase of crystallization.

Here it must be added, that in the phenocrysts of augite there is rarely found such a phenomenal crystal as is illustrated in Fig. 6, Pl. XII, which shows the face of clinopinacoid. It should be noticed that that part of the face which is covered by the diagonals drawn through the antagonistic angles of the rhombic crystal face is particularly prominent and presents a smooth shining appearance while the remaining part of the face between these diagonals is rough, sunken and imperfectly developed. This imperfect crystal makes us recall skeleton crystals (Fig. 7, Pl. XII) of monoclinic pyroxene which are found in glassy augite-andesite of Mt. Pipe in Iwôjima, to which Dr. Peterson called special attention.

In a word, the lava of the new island in question was vitrophyric rock of intermediate composition rarely found in the volcanoes of our country, and bore family resemblance to the glassy andesite of Mt. Pipe in Iwôjima described by Dr. Petersen, in the crystal habit and the optical properties of its plagioclase, in the nature of its augite, especially of its skeleton crystal, in its abounding in apatite, and also in the nature of its ground-mass. But on the other hand it was different in every respect from the agglomeratic andesite of Kita-Iwôjima.

Disappearance of the New Island.—On the 16th of June, we sailed toward the point where the new volcano was said to have lain, but to our wonder and disappointment nothing of the island came in sight. At two in the afternoon, when our steamer at last proceeded to a spot 5 nautical miles distant from Minami-Iwôjima, Captain Nielsen discovered at a great distance something like the white crest of an angry wave dashing against a reef. As we drew near, an island became

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visible by aid of a telescope. It looked like the back of a whale half hidden by the waves, and we were given to understand that the new-born island which had been reported to be 480 feet high was now reduced to a low reef of less than 10 feet high (Fig. 2, 3, Pl. IV.).

The Captain, calculating the position and size of the sinking island at 3 nautical miles N.N.W. thereof, found that it was situated 24° 16′ 30″ north latitude and 141° 30′ east longitude, and 3 nautical miles north-east of the coast of Minami-Iwôjima, and that it was 8 to 10 feet high and 1500 feet long (Fig. 2, Pl. IV).[1] When seen from the west at the same distance, the island lessened in length nearly one third (Fig. 3, Pl. IV), from which we may infer that the present island is elliptical, somewhat longer east and west. This shape corresponded to that of the former head of the island described in the explorers' report, and reminded us of its form of half an year before. This is a noteworthy fact since it will prove a help to us in considering the cause of the disappearance of the island.

The explorers' report says it was on the 5th of December 1904, that the New Island was first discovered by the inhabitants of Iwôjima, and it was on the 1st of February 1905, that an exploration and survey was effected by them. Thus we see that during the one-hundred and thirty-six days following the latter date (Feb. 1st), a volcanic island, 480 ft. high and 3 miles in circumference, was demolished almost to nothing. The speediness of its demolition is really beyond conception. What is more, some of the inhabitants of Iwôjima told us that they had already lost sight of the New Island in May. If that was really the case, the island was even more short-lived.

Now, there are three chief actions to be considered as the causes of the extinction of volcanic islands; namely, the action of the waves, its own explosion and depression of the volcanic body. Of these three, the first is known to have not infrequently brought about a phenomenon of this sort up to the present day. Graham's Island or Isola Ferdinandea in the Mediterranean Sea, and Falcon Island and Metis

1) My sextant measurement, however, set its length at less than 500 feet.

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Island in the Pacific Ocean furnish remarkable instances. These islands were, however, nothing but accumulations of very loose cinders ejected during their own eruptions, and no wonder that they should have been affected by the waves so soon. Yet, Falcon Island (2 miles long and 250 feet high, heaved up in October 1885 and submerged in 1897) which was similar to the New Island in shape and size, vanished after 12 years, and Metis Island (150 feet high and created in 1875) still smaller as it was, passed away in no less than 24 years. There has been no island so short-lived as the New Island. However, it is not to be supposed that the New Island was composed of more fragile substances than the said two islands; and this consideration will naturally dispose us to think that the speedy extinction of the island in question cannot properly be ascribed to the bare action of the waves.

Then the question arises, is it attributable to the explosive action of the volcano? As was the case with Bandaizan and Krakatoa volcano, this action has often demolished a huge mass of mountain with inconceivable force and suddenness; and it may seem to be the very explanation for the present question. But further consideration will make it clear that this is far from being the case since there is not a single proof of the island being subjected to such explosion, and if there had been any such terrible eruption at all, the inhabitants of Iwôjima who witnessed the rising of the New Island would certainly have taken notice of it, and even if dense clouds or fogs prevented the sight, they must have heard the thunderous noise of the explosion or felt shocks of earthquake. Another point that demands our notice is that that part of the island which remained above the sea, as we saw it, was almost of the same shape as is described in the islanders' report, which fact seems to prove that the island kept the same shape until its submergence, scarcely experiencing any considerable explosion. Mr. Satô, one of my fellow-explorers, being told in the Bonin Islands that three weak earthquakes were felt at that island on the 12th of April, 9th and 21st of May respectively, and a strange noise like a distant gun was often heard from the west on the 18th of May, sus-

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pected that these phenomena might have had some connection with a supposed explosion of the island. But I am not inclined to agree with him, because, if an earthquake had occurred at the island, it is not to be supposed that it should not have been felt in the Middle and North Sulphur Islands only 30 or 70 nautical miles distant from the New Island, but in the Bonin Islands only which is so much as 200 nautical miles therefrom. The above conjecture will sound even more absurd when we reflect that he must have meant a volcanic earthquake, which is as a rule comparatively small in extent, and that he supposed it to have taken place in a new volcano which belongs to the same zone as the Middle and North Sulphur Islands. From these considerations, it is safe to say that the earthquakes felt in the Bonin Islands had nothing to do with the New Island, but were special ones occurring in the vicinity. Thus, there is not a single fact that proves any explosion in the New Island in connection with its disappearance.

Lastly, the action of depression demands our consideration. When a great mass is poured forth in volcanic eruption, the result will follow that density in that part will become lessened and the pressure will consequently decrease; then it is quite possibile that the whole or part of the volcanic body may fall down by its own weight. It is said that large craters such as those of Aso and Hakone, are produced by the depression of part of the crater. According to Mr. Iki,[1] the extension of the crater of Aso now unparalleled in dimension is ascribable to the outflow of an immense mass of "Aso-lava," which, he thinks, caused a depression of the vent. If this is true, it may safely be said that the fall of a crater wall is possible in submarine volcanoes as well as terrestrial. The only difference is this, that since in the case of a terrestrial volcano there is no unerring standard with which to compare its fluctuation, little or no attention is paid; while in the case of marine volcanoes sea-level serves as an unmistakable standard.

In short, although I have no absolute proof or datum to demon-

1) Geology of Aso Volcano, by T. Iki. Reports of the Imperial Earthquake Investigation Committee in the Japanese Language. No. 33.

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strate the vanishing of the New Island, having found no opportunity to make any personal exploration of it, I think I may safely ascribe the phenomenon to the action of the waves, of which we have so many instances. Nevertheless, I rather hesitate to say this was the only cause of its submergence, considering its exceptional rapidity; and if there was any cause besides the action of the waves, it must be either explosion or depression; but since in this case there is no proof of explosion, the occurrence of which would naturally have attracted the attention of the people in Iwôjima, I venture to say that the phenomenon in question was due to a depression of the volcanic body (which is in most cases apt to escape our notice) as well as the action of the waves.

SUMMARIES.

1. Considering both its geographic position and the nature of its ejecta, it is clear that the New Island was a volcano belonging to the same volcanic line as the other three principal volcanic islands of the Iwôjima group.

2. The eruption was no doubt explosive, and ejected, most of all, the fine débris of pumice at the first stage of eruption, but afterwards vitrophyric lava composed half of obsidian and half of pumice. And though it is certain that other substances composed the body of the island, it remains doubtful whether they were subaerial ashes loosely accumulated or tuffs previously consolidated at the sea-bottom before the eruption; the latter being the case with Motoyama in Iwôjima. Pumice fragments transformed from lava came drifting to the shore of the island and formed a gravel-beach, 120 or 180 feet wide.

3. Petrographically the lava is of olivine-augite-andesite. It greatly resembles, as a whole, the glassy lava of Mt. Pipe in Iwôjima. and widely differs from the agglomeratic lava in Kita-Iwôjima.

4. In point of materials and structures, as Peel Island and Hillsborough Island in the Bonin group are of two different volcanic types, so the volcanic islands of the Iwôjima group may be divided into two

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different types. To speak more concretely, Minami-Iwôjima and Kita-Iwôjima (San Augustino Is. and San Alessandro Is. respectively) which became inactive long ago, are composed of the same kind of agglomeratic rock of Hillsborough Island type, are very similar in mountain shapes, and seem to belong to one volcanic type peculiarly their own. On the contrary, Mt. Pipe, Motoyama, the New Island and the submarine volcano in the neighborhood of Kita-Iwôjima, which are all still active and explosive, eject chiefly glassy ashes and rarely vitrophyric lavas, but never to such an extent as to augment themselves. Mt. Pipe alone, however, poured forth a comparatively great quantity of lava, so as to assume a conic shape. These four volcanoes are of the other type.

5. On the 1st of February 1905, the New Island was 3 miles in circumference, 200 acres in area, and about 480 feet in height; but, on the 16th of June of the same year, that is, only 136 days after the above-given date, it was reduced to a low reef, only 1500 feet long and less than 10 feet high. The causes of its subsidence remain uncertain, but the chief of them seems to be the encroaching action of the waves. But what brought its submergence so soon? That is the question. It may be that the aforesaid agency was accompanied by a depression of the crater rim.

According to Mr. Hagiwara, Captain of the *Hyôgomaru* which sailed about the adjoining sea of Minami-Iwôjima in the course of June of the present year, the New Island was entirely buried in the sea, and though he inspected the spot where the island had once lain and also its neighborhood, he saw nothing unusual in the condition of the waves. This leaves no room for doubt that the island was but ephemeral as we had expected and that it had sunk down to the depth of more than 10 feet below the surface of the sea.

Tokyo Imp. Univ.
Nov., 1906. T. Wakimizu.

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APPENDIX.

Eruption of a Submarine Volcano Near the Bayonnaise Rocks.

As I have stated in the present paper proper, I was shown the pumice blocks that had come drifting to the Bonin Islands for some time past and found that they are of several different kinds. I was disposed to think that there might have been eruptions of some unknown submarine volcanoes near the "Fuji volcanic zone"; and I found afterwards that I had not been mistaken in this consideration or rather surmise, for I got a report from the crew of the *Okinawamaru*,[1] who chanced to be at work near the scene, to the effect that on the 14th April of last year there was a great eruption of a submarine volcano near the Bayonnaise Rocks,[2] an isolated islet in the sea between Aogashima and Smith Rock. A description of the eruption which is said to have been given by Mr. Kajiura, Engineer of the Department of Communications, who was on board the ship, runs as follows:

"The men in the *Okinawamaru* while working near 31° 59′ north latitude and 140° 7′ east longitude on the 14th of April last year, about 11 o'clock a.m., saw a huge volume of white smoke rising up near the Bayonnaise Rocks, at a spot less than 10 nautical miles distant to the S. S. E.—that is, about 20 ri southeast of Aogashima. By the rough measurement of the crew, the pillar of smoke seemed to be more than 300 feet in diameter and to range from 400 feet to 1000 feet in height, according to the power of the wind and the eruption. The grand spectacle presented by the continuous ejection of white vapor was absolutely beyond the power of pen or tongue to describe. The rocks in front were entirely hidden from view by smoke,

1) *Okinawamaru* is a submarine-cable vessel belonging to the Department of Communications.

2) The Bayonnaise Rocks consist of three big rocks and many small reefs, all of pointed conical shape, of which the highest is less than 30 ft. above the sea-level.

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except at short abatements of ejection. Smoke did not cease arising till the *Okinawamaru* left there the following day. There was no knowing when the eruption had begun; but, as the phenomenon was not noticed on the 4th, it probably began abruptly after that day. I regret that we could not approach it, as our duty called us in a different direction, but I saw pumice rising in a great quantity from the spot of eruption and floating eastward with the current. It covered the sea to the breadth of nearly two miles, looking like a large sheet of white cloth spread, or like innumerable white foams floating."

The collected samples of the above-mentioned pumice was put at my disposal through the kindness of Prof. Kotô. They are all of pure white colour, less than one centimeter in diameter, and contain black augite and transparent colourless feldspar as phenocryst. Microscopic examination of thin sections shows that their air-vesicles are not long and flat as in common pumice, but elliptical pores ranged side by side, and what is most remarkable and curious is that some larger and longer vesicles are ranged radially round phenocrysts of feldspar and augite (Fig. 4, Pl. X). This peculiar arrangement of vesicles may be explained by the following consideration:—

It is obvious that the pumice in question is basic, considering that its phenocrysts are all of basic minerals like bytownite and hypersthene as stated below, and that magnetite is contained in a comparatively large quantity. It is generally accepted that basic magma is viscous and is slower in cooling and consolidation than acid magma; but, no doubt, as the magma was ejected into the sea-water, a better conductor of heat than the atmosphere, it was naturally cooled and consolidated in less time than in the atmosphere in spite of its being basic, and was turned in to spongy pumice. Now, this magma contained phenocrysts already crystallized and as it undoubtedly emitted latent heat as it grew cool, a small part surrounding the crystal kept some heat and was in a semi-fluid condition even after the other part became consolidated. Thus we see the cooling and consolidation of this small part was completed a moment later than the others; and while this

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was going on, the air-bubbles of a comparatively small number contained therein being stretched by the attraction passing between the central phenocryst and the surrounding walls, assumed the present tubular form and ranged themselves radially. I must confess that this explanation is not quite satisfactory even to myself and further study is necessary for the complete solution of the problem.

As porphyritic ingredients, augite, feldspar and magnetite occur in idiomorphic crystals, each less than 1·5 mm. The feldspars are fresh and transparent, and have but a few inclosures of colourless glass in the shape of negative crystals and acicular crystals of apatite; and zonal structure may be recognized by its manner of extinction. Carlsbad twin is frequent but albite twin is rare. The extinction angle on oP face is about −24.° Perhaps the feldspars are of bytownite. The augites belong to the rhombic family and occur in prismatic crystals. They are strongly pleochroic and vary in colour between a greenish yellow, b yellowish brown and c olive-green. Perhaps they are of hypersthene. Feldspar and augite are often combined into aggregate, together with magnetite. In respect to the quantity of phenocryst, feldspar comes foremost, then augite and then magnetite. Besides, there are non-transparent masses which appear to be absorbed residue of some minerals. They are surrounded by radially arranged vesicles as in the case of phenocrysts of feldspar and augite.

Thus, microscopic examination shows us that this rock is hypersthene-andesite. Last of all, let me add that this pumice quite differs from that of the New Island from the petrographical point of view.

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PLATE I.

The Geographical Position of Iwôjima (Sulphur Is.) Group.

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Plate I.

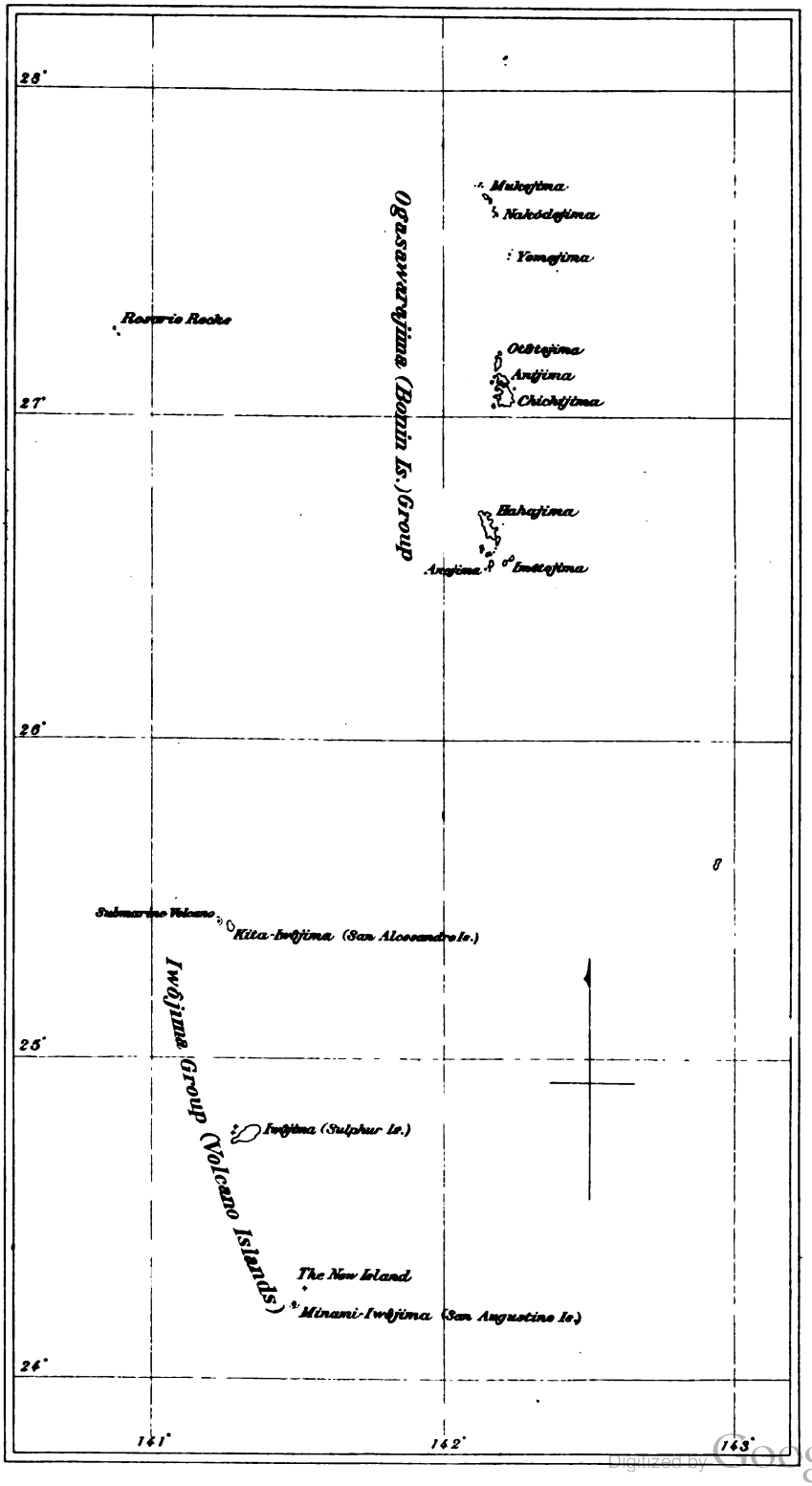

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PLATE II.

Kita-Iwôjima (San Alessandro Is.)

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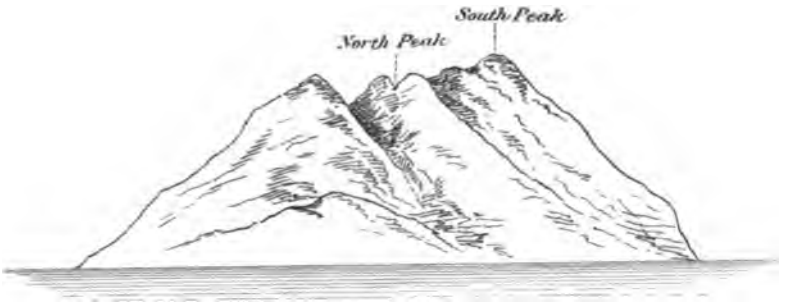
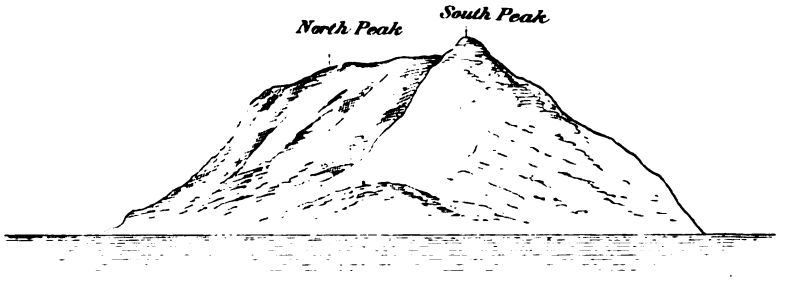
Plate II.

Fig. 4.



Kita-Iwôjima. S 50° E. 1·5 Mile (Naut.)

Fig. 5.



Kita-Iwôjima. Due S. 1·5 Mile (Naut.)

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PLATE III.

Iwôjima (Sulphur Is.) or Naka-Iwôjima.

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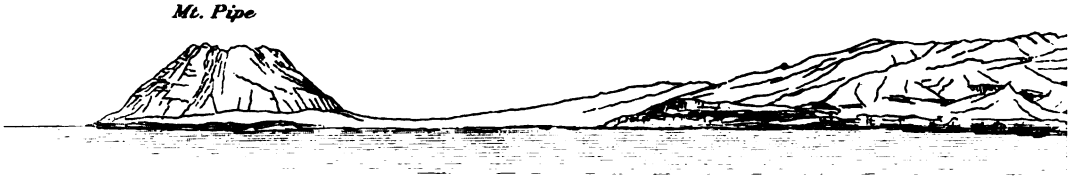
Plate III.

Fig. 3.

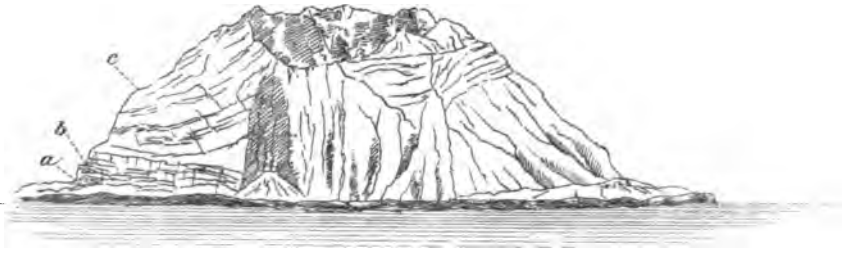
Iwôjima, E. 2 Miles (Naut)

Fig. 4.



Iwôjima. N.W. (Original Sketch of F

Fig. 5.



Mt. Pipe. (Original of Prof. Kikuchi)

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PLATE IV.

Minami-Iwôjima (San Augustino Is.) and the New Island.

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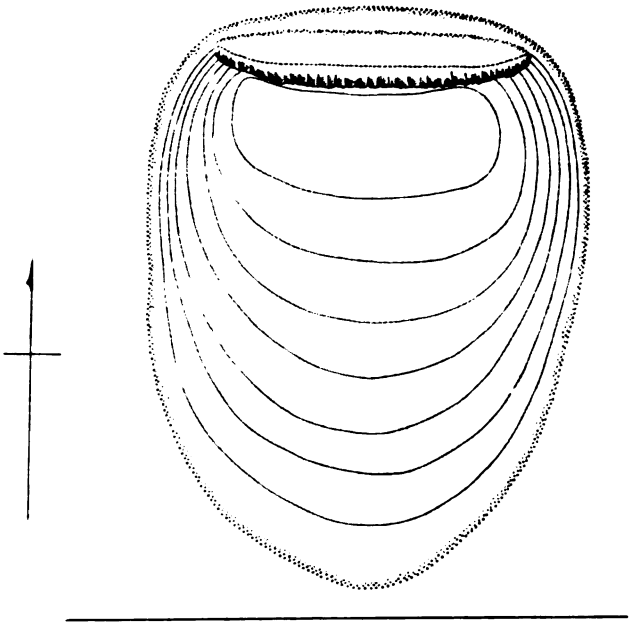
Plate IV.

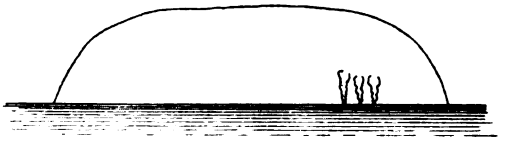
Fig. 4.

Map of the New Island drawn by the Explorers of Iwojima in Feb. 1st, 1905.

Scale 1:12000.



Side View from the North.



Side View from the West.

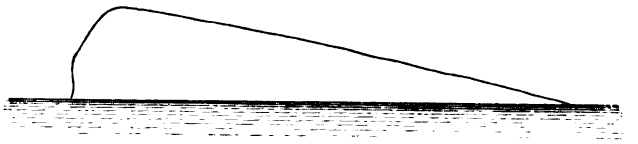


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PLATE V.

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Fig. 1. Kita-Iwôjima (San Alessandro Is.). N.N.W. 3 Miles (Naut.). Photographed by the Writer in June 16th, 1905.

Fig. 2. Minami-Iwôjima (San Augustino Is.). S.E. 2 Miles (Naut.). Photographed by the Writer in June 16th, 1905.

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Fig. 1.

Fig. 2.

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PLATE VI.

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Fig. 1. Coral Reefs on the Summit of Motoyama in Iwôjima. Solfatara on the Left.

Fig. 2. "Tischstein" and Wave-worn Terraces in Iwôjima.

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Fig. 1.

Fig. 2.

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PLATE VII.

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Fig. 1. Reef-forming Coral (Stylophora sp.) with Black Coating on the Summit of Motoyama in Iwôjima.

Fig. 2. Ditto with Bleached Surface.

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Fig. 1.

Fig. 2.

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PLATE VIII.

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Plate VIII.

A block of the lava of the New Island, investigated by the author. This block is pumiceous in the upper part, and gradually passes into obsidian in the lower part. About $\frac{7}{10}$ times of the natural size.

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Plate VIII.

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PLATE IX.

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Plate IX.

Fig. 1. Obsidian (Olivine-augite-andesite) of the New Island. × 16.

An irregular octagon on the left-hand side of the figure is the section of monoclinic augite, cut near oP. Prismatic cleavage is distinct. The periphery is fringed by augite-microlites and other minute opaque substances. A cubic colourless crystal on the right side opposite to the one mentioned above, is plagioclase (oligoclase). It contains brown glass as inclosures crowding the centre. Rod-like individualized substances universally scattered through the ground-mass, are of microlites of light yellow monoclinic augite.

Fig. 2. Ditto, much more magnified. × 147.

Cross section of monoclinic augite in the centre. Among the augite-microlites in the ground-mass, some penetration twins of stellate form are seen.

Fig. 3. Agglomerate-forming augite-andesite in Kita-Iwôjima. × 50.

The colourless rectangular phenocrysts seen in abundance are of plagioclase (anorthite). The rhombic crystal at the centre is of altered monoclinic augite. The ground-mass is holo-crystalline, and is composed of lath-shaped plagioclase, augite grains and magnetite granules.

Fig. 4. Dyke augite-andesite in Kita-Iwôjima. × 50.

The large colourless phenocryst of tabular form is plagioclase that contains abundant glass-inclosures. The ground-mass is holocrystalline, consisting of microlites of feldspar, augite and magnetite, together with a few glass bases.

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Plate IX.

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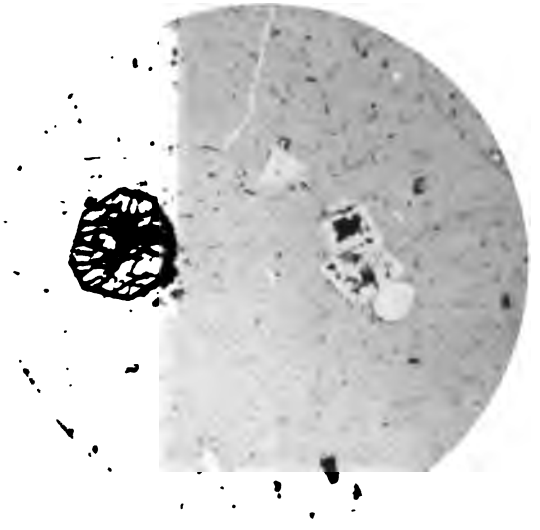

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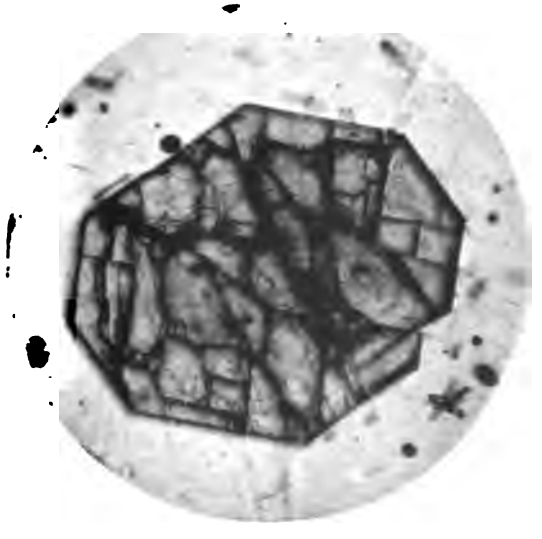

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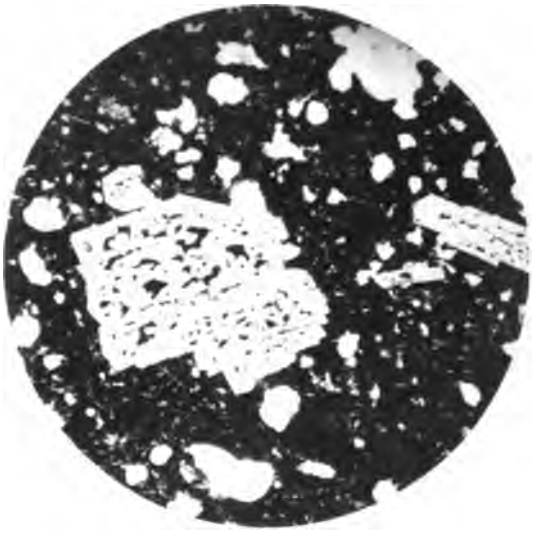

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PLATE X.

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Plate X.

Fig. 1, 2. Monoclinic augite in the pumice of the New Island, separated by Thoulet's solution. × 50.

Crystals are well defined. In Fig. 2., a crystal is twinned on $\infty\bar{P}\infty$.

Fig. 3. Brachypinacoidal section of oligoclase in the pumice of the New Island. × ca. 30.

Take notice of the development of basal cleavage and zonal arrangement of glass-inclosures.

Fig. 4. Section of the pumice ejected by a submarine volcano near the Bayonnaise Rocks. × 50.

This figure shows the radial divergent arrangement of air-vesicles around a well-defined feldspar-phenocryst.

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Plate X.

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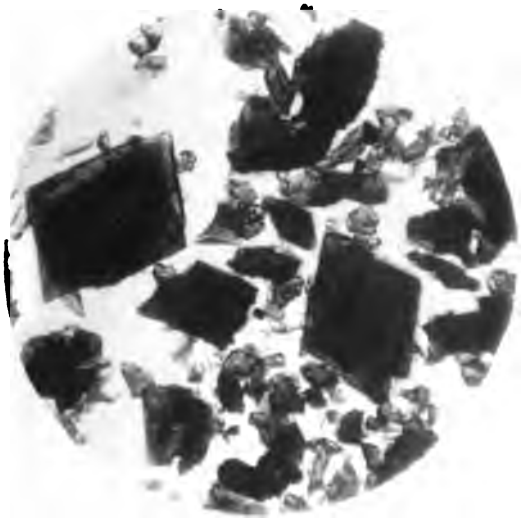

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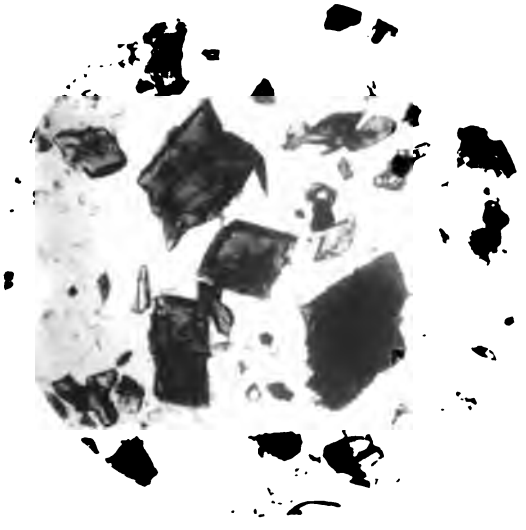

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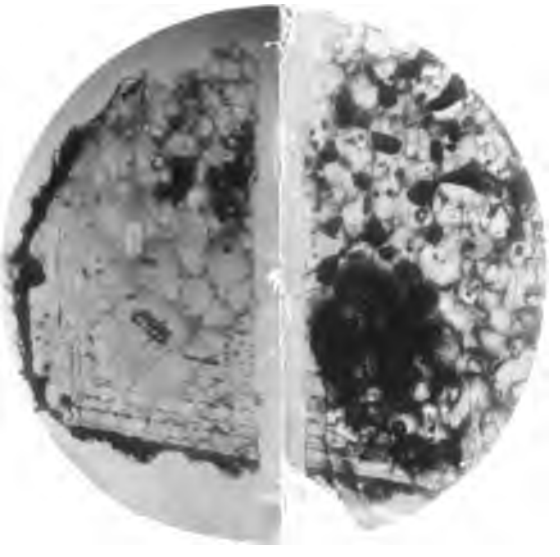

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PLATE XI.

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Plate XI.

Fig. 1. Apatite crystals in Motoyama-tuff of Naka-Iwôjima.

They contain remarkable glass-inclosures, elongated in the direction of the principal axis. Most of the inclosures possess one or more immovable air-bubbles.

Fig. 2. Apatite crystals in the pumice of the New Island.

Compare them with those in the preceding figure.

Fig. 3, 4, 5, 6. Well-defined crystals of monoclinic augite in the pumice of the New Island.

$s = -\mathrm{P}$, $b = \infty\breve{\mathrm{P}}\infty$, $m = \infty\mathrm{P}$, $a = \infty\bar{\mathrm{P}}\infty$.

Fig. 7. Twin-crystal of ditto. Twinned on $\infty\bar{\mathrm{P}}\infty$. This figure also shows the mode of occurrence of apatite- and glass-inclosures in the crystal.

Apatite needles and elongated glass-inclosures are so placed that their longitudinal axes lie parallel to some domal faces of the crystal.

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Plate XI.

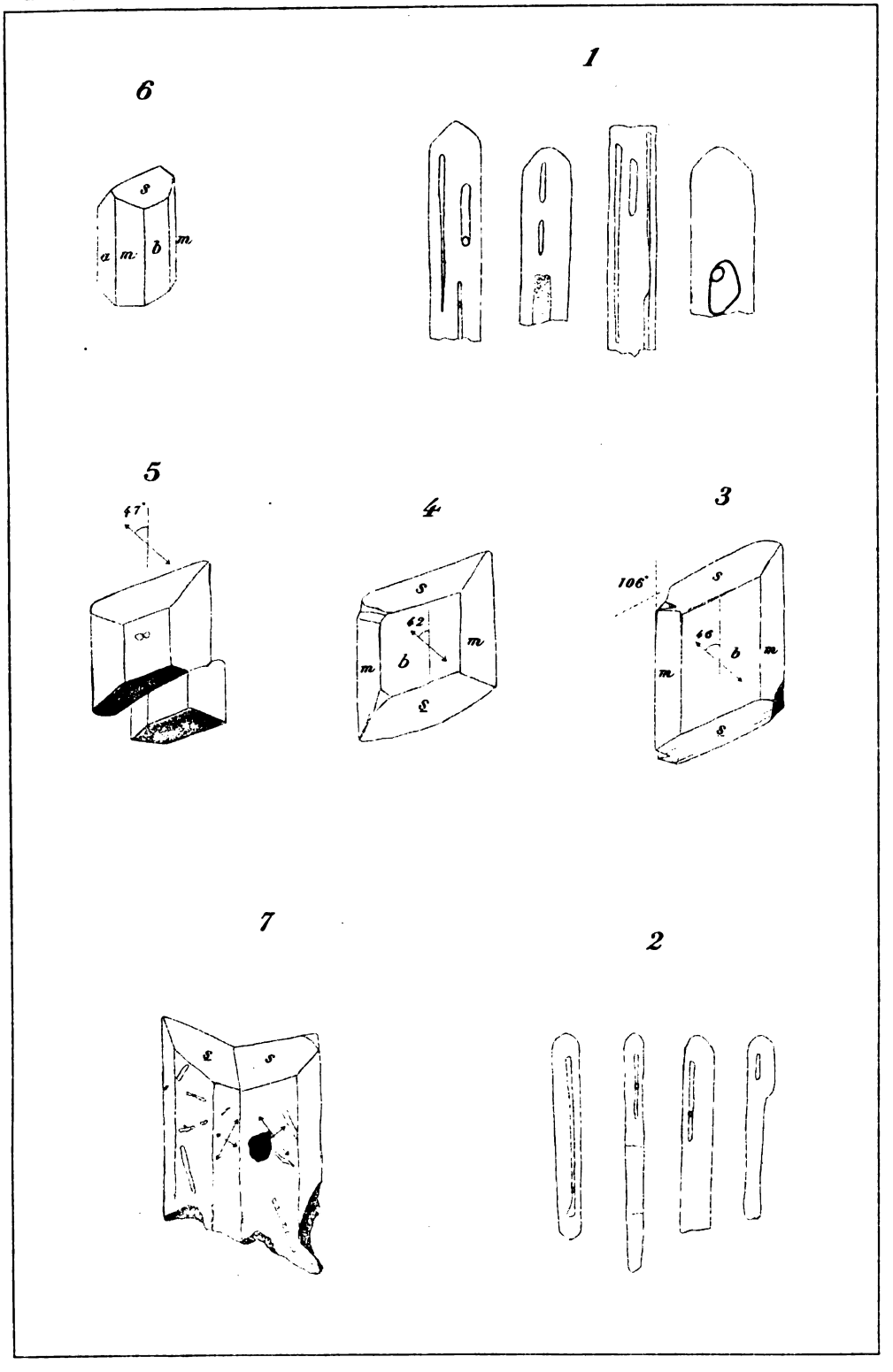

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PLATE XII.

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Plate XII.

Fig. 1. Olivine in the pumice of the New Island.

The crystal is considerably corroded, and sometimes intruded by ground-mass.

Fig. 2. A basal section of oligoclase in the pumice of the New Island.

Apatite needles and coloured glass-inclosures are abundantly enclosed.

Fig. 3. Some of the glass-incloures in ditto.

The edge of the inclosures in part runs parallel to some crystal faces of the encloser; they are thinly flattened along the cleavage faces of the latter.

Fig. 4. Colourless hexagonal scales of muscovite (?) coating the face of orthoclase in Motoyama-tuff as the decomposition product of the latter.

Fig. 5. Microlites of monoclinic augite (greatly magnified) scattered in the ground-mass of the obsidian of the New Island. Both extremities of prisms are commonly indented or irregularly truncated. They are often twinned in various manners, as shown in the figure.

Fig. 6. A peculiar crystal of monoclinic augite in the obsidian of the New Island. The two diagonals connecting opposite angles mark a well-developed shining face, while the remaining part of the crystal face is slightly grooved and of dull lustre.

Fig. 7. Skeleton crystal of augite in the glassy augite-andesite of Mt. Pipe, Naka-Iwôjima, described by Dr. Petersen. (This is a original figure of Dr. Petersen.) Note its near resemblance to the preceding.

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Plate XII.

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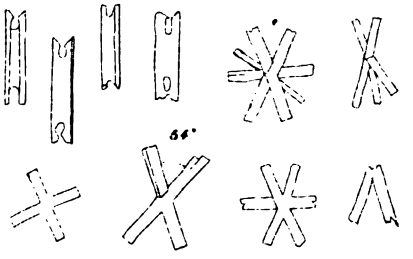

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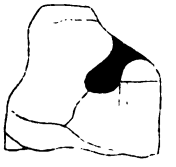

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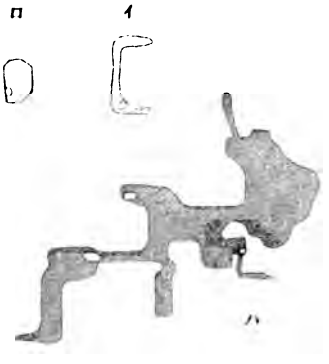

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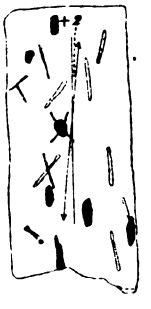

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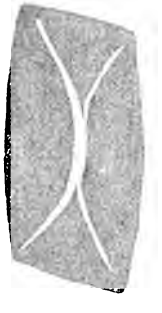

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